Stratigraphical and Microfacies Analysis of the Late Eocene-Early Oligocene Sucession of Jabal Hafeet, UAE

by

Hany Farouk El-Sahn

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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In

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King Fahd University of Petroleum and Minerals (Saudi Arabia), 1992

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بسم الله الرحمن الرحيم

In the name of Allah, the Beneficient, the Mercicul

"And say: My Lord! Increase me in knowledge!"

(Taha - 114)

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN 31261, SAUDI ARABIA
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This thesis, written by **Hany Farouk El-Sahn** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **GEOLOGY.**

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All praise be to Allah, Lord of the Worlds, the Almighty with whose gracious help it was possible to accomplish this work.

My most sincere appreciation and deep gratitude are here extended to Prof. Z.R.El-Naggar, my thesis advisor, for suggesting this topic, laying out the plan of research, providing the samples, the thin sections and most of the references. I would like to thank him particulary for his painstakingly efforts revising the manuscript as well as his valuable advice and fatherly support through out all phases of this work.

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Last but not the least, I would like to extend a word of gratitude to my friends in Dhahran and Jiddah, and to my brother in Qatar for supporting me morally and financially during the last period of my stay at KFUPM.

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THESIS ABSTRACT

Name of Student : **Hany Farouk El-Sahn**
Title of Study : **Stratigraphical And Microfacies Analysis Of The Late Eocene - Early Oligocene Succession Of Jabal Hafeet, U.A.E.**
Major Field : **Geology**
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Jabal Hafeet is the only known locality in Arabia with fossiliferous, marine, Late Eocene-Early Oligocene outcrops. This succession was studied in thin section for both its stratigraphical and microfacies analysis. A total of five distinctive microfacies have been recognized and used to interpret both the age and the paleoenvironmental conditions of deposition of the succession which is proved to be of Late Eocene - Early Oligocene age. A rich assemblage of larger benthonic foraminiferid remains (mainly Nummulitids) and a sparse record of planktonic foraminiferid and other remains have been identified. The succession represents a shallowing upward carbonate cycle moving from open marine shelf to shelf edge conditions.

The succession is here correlated with both the Dammam and the Asmari Formations which have long been established in the Arabian Gulf stratigraphy. Although the type section of the Dammam Formation is only of Middle Eocene age and is truncated by the post-Dammam unconformity, it is here suggested to expand the term Dammam to include Late Eocene successions of similar facies in the region. The Dammam *sensu lato* as here defined includes carbonate facies, of shelf conditions rich in larger benthonic foraminiferid remains (e.g. Nummulitids) of Middle to Late Eocene age. It was deposited in a sedimentary cycle that followed the Paleocene - Early Eocene Umm Al-Radhuma / Umm Al-Rua'us (Rus) Formations. In deeper water facies (such as the subsurface of the U.A.E.) the three formations pass laterally into the more shaly and marly Pabdeh Formation. Nevertheless, the overlying Asmari Limestone is generally represented by reefal facies. This testifies for the regression of the sea off Arabia during the Late Paleogene time. Such regression can be explained by the world wide low sea stand during the Late Oligocene (Chattian) time, but it can also be connected with the deformation of the sedimentary basin during both the Omani and Zagros Orogenics. Recently introduced names for rock units in the succession such as the Hafeet, Senayeiah and Al Jaww are believed to be superfluous and are thus here, dropped.

MASTER OF SCIENCE DEGREE

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Dhahran, Saudi Arabia.

خلاصة الرسالة

اسم الطالب : هاني فاروق الصحن
عنوان الدراسة : دراسة طباقية و سحنية دقيقة لتتابع من عمر الأيوسين المتاخر الى الأوليجوسين المبكر في جبل حافيت بالإمارات العربية المتحدة .
التخصص : جيولوجيا
تاريخ الدرجة : يناير ١٩٩٣

جبل حافيت هو الموقع الوحيد فى شبة الجزيرة العربية الذى تظهر فيه على سطح الارض صخور بحرية تابعة لزمن الايوسين المتاخر و الاوليجوسين المبكر. ولقد تمت دراسة هذا التتابع فى قطاعات صخرية رقيقة و ذلك بغرض التحليل الطباقى و السحنى. و فى ذلك امكن التعرف على خمسة سحن دقيقة متميزة تحتوى كل منها على مجموعة غنية من بقايا المنخربات القاعية الكبيرة بالإضافة الى عدد قليل من بقايا المنخربات الهائمة واحافيراخرى عديدة . و قد استخدمت هذه البقايا الحياتية فى تحديد عمر التتابع وفى اثبات انه يمثل دورة ترسيب بحرية ضحلة تغلب عليها الرواسب الجيرية و تزيد فى الضحالة باستمرار من اسفل الى اعلى حيث تحولت من ظروف بحرية مفتوحة الى اخرى حول حواف الرصيف القارى. هذا و قد تمت مضاهاة التتابع بكلا من متكونى الدمام بمعناه الواسع و الاسمرى. و الدمام بمعناه الواسع يعرف فى هذة الدراسة بانه وحدة صخرية تمثل بسحنة جيرية غنية ببقايا المنخربات القاعية الكبيرة رسبت حول الرصيف القارى فى زمن الايوسين الاوسط الى المتاخر و ذلك على الرغم من كون القطاع النموذجى لمتكون الدمام يتوقف فى العهد الايوسينى الاوسط و ينتهى بسطح لاتوافقى كبير. و يستدل مما تقدم على تشوه الحوض الترسيبى خلال الحركات البانية لجبال عمان و زاجروس بالإضافة الى تراجع البحر عن ارض شبه الجزيرة العربية على الأقل خلال العهد الوليجوسينى المتاخر (الشاتيان). و قد اسفرت هذة الدراسة ايضا عن ان اسماء الوحدات الصخرية التى قدمت مؤخرا للتتابع مثل متكون حفيت و الصناعية و الجو هى اسماء لاداعى لها و بالتالى فقد اسقطت.

درجة الماجستير فى العلوم

جامعة الملك فهد للبترول و المعادن
الظهران, المملكة العربية السعودية

This thesis is dedicated to

my beloved parents, brother and sister,

who have supported me and still do...

I. INTRODUCTION

Early Paleogene rocks are well developed in both surface and subsurface sections allover northern, northeastern, eastern and southern Arabia. These represent parts of the Paleocene as well as the Early and Middle Eocene, {or almost half of the total duration of the Paleogene Period which is estimated to be about 42 m.y. (66.4 Ma to 24.4 Ma)}. The succession which is generally included under the term Hasa Group is truncated at its base by the Cretaceous / Paleogene unconformity and at its top by the Early Eocene / Miocene unconformity. The duration of this is in the order of 8 - 16 m.y. allover most of Arabia and represents one of the major unconformity surfaces in the sedimentary succession of the Peninsula. Consequently, no fossiliferous, marine, Late Eocene or Oligocene rocks have been encountered in this region except in the subsurface of the U.A.E. and in a small outcrop at the western foothills of the Omani Mountains known as Jabal Hafeet. Fossiliferous, marine, Late Eocene - Oligocene rocks have also been recorded in both mainland and offshore Iran, in northern Iraq and in Syria.

Apparently, any Late Eocene - Early Oligocene sediments deposited in the region were later on eroded during the world wide, Late Oligocene (Chattian) low sea stand. However, the fact that fossiliferous, marine, Late Eocene -

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N.B.) Ma (*Mega annum*) = Million years before present.

Oligocene rocks were limited to the extreme periphery of the Peninsula can suggests an overall retreat of the sea off the Arabian plate except for a small embayment which occupied the Oman Mountains foredeep, extending from western Iran to the central part of the Omani desert. Such regression can be attributed to an upwarping of the eastern margin of the Arabian plate, as a resulting of a collision with the Neo-Tethys oceanic crust, that preceded the obduction of Oman Ophiolite and the formation of a number of flexures.

This has emphasised the importance of the Jabal Hafeet section as the only known outcrop in Arabia with a more or less complete Paleogene succession in which both the Late Eocene and the Oligocene times are represented by fossiliferous, marine rocks. Accordingly, the present research work was, proposed with the hope that it can throw some light on the Late Paleogene Period in Arabia, its sedimentary succession, fossil content, paleoenvironmental conditions of deposition and facies distribution.

I.1 Objectives of the study

The main objectives of the proposed study are to carry out a stratigraphical and microfacies analysis for the Late Paleogene surface section of Jabal Hafeet, U.A.E. and to correlate it with corresponding rock units in the region wherever possible. The collected data can then be utilized for the interpretation of both the age and paleoecological conditions of deposition of each microfacies in the succession, for its regional correlation and for the interpretation of the geologic history of the area during the Late Paleogene time. such objectives can be summarized as follows:

1) Reviewing the Paleogene succession in Arabia, with emphasis on the Late Paleogene regressive phase.

2) Lithostratigraphical analysis of the only known Late Eocene / Oligocene surface section in Arabia (the Jabal Hafeet section).

3) Microfacies analysis of the studied section.

4) Interpreting the age of each of the recognized lithostratigraphic and microfacies units.

5) Paleo-ecological interpretation of the recognized microfacies.

6) Identification of the recorded microfossils in each of the recognized rock units.

7) Interpreting the geologic history of the area during the Late Eocene - Oligocene time.

I.2 Location and Geological setting

The Jabal Hafeet area is located south of Al Ayn town, in the south eastern part of Abu Dhabi, the U.A.E. (figs.1,2,3). The area is nearly 21 km long and 12 km wide and hence cover an area of about 250 square kilometers. It has been subjected to several tectonic phases that resulted in the deformation of the sedimentary sequence in the form of folding, faulting as well as jointing.

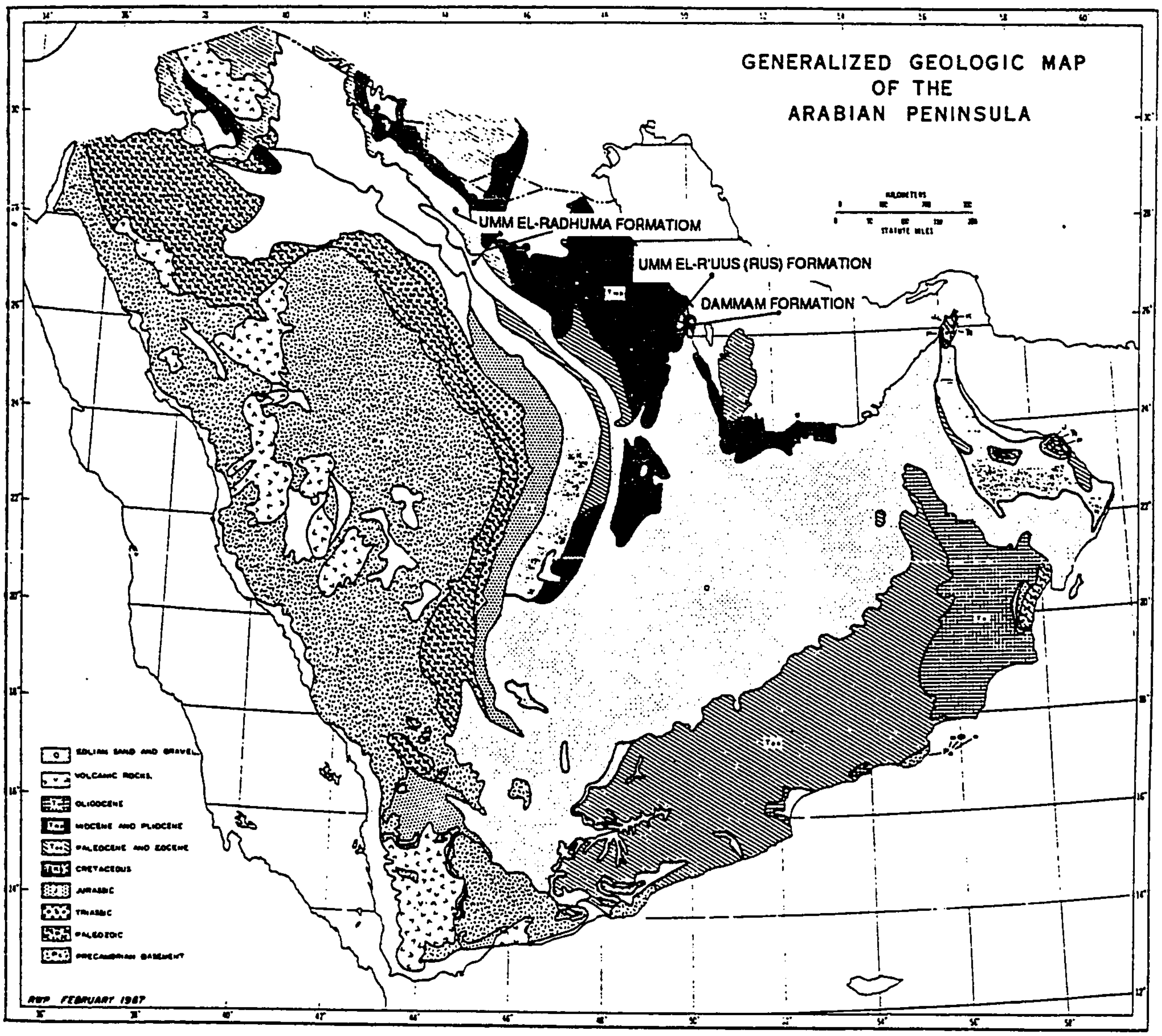


Fig.1 : Generalized geologic map for the Arabian Peninsula showing the locations of the Paleogene type localities in Saudi Arabia (After Powers, 1968).

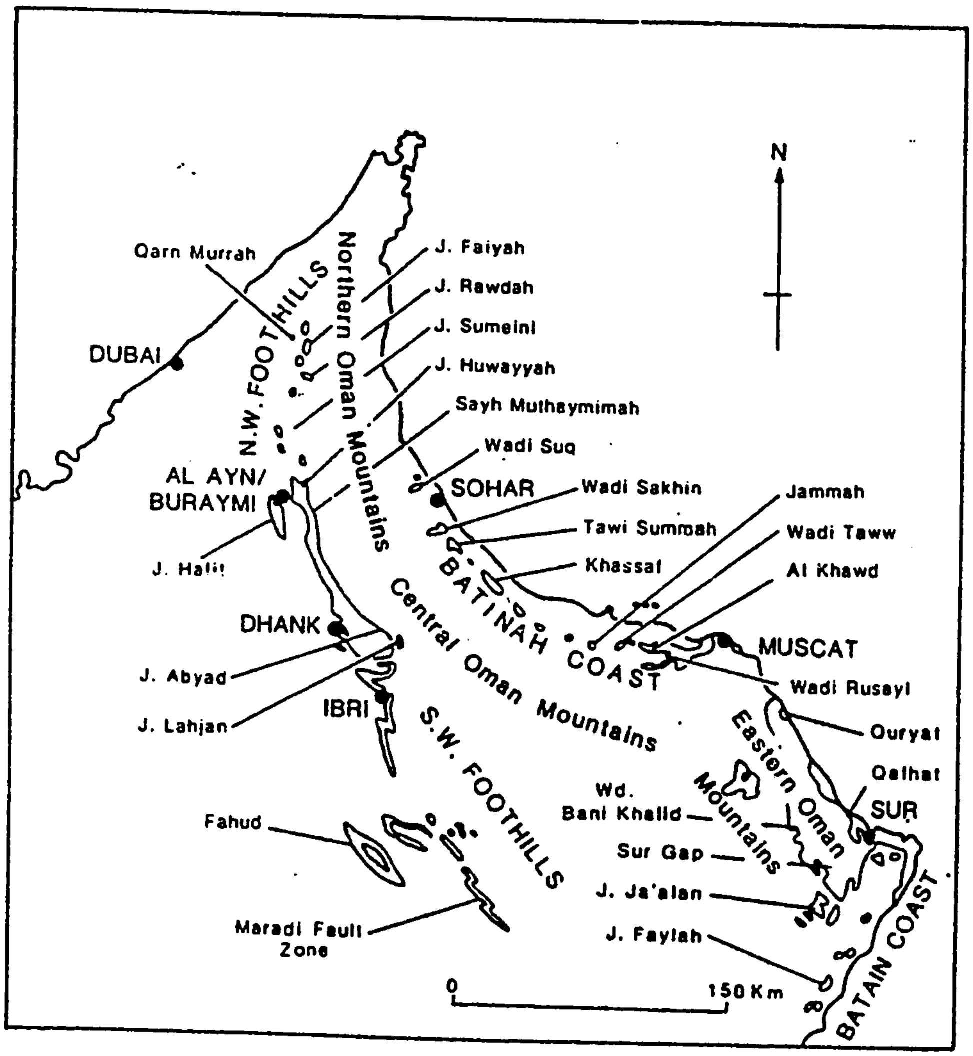


Fig.2 : An index map showing the locations of both Jabal Hafeet and some type sections mentioned in the text for the Oman Mountains (From Nolan and others, 1990).

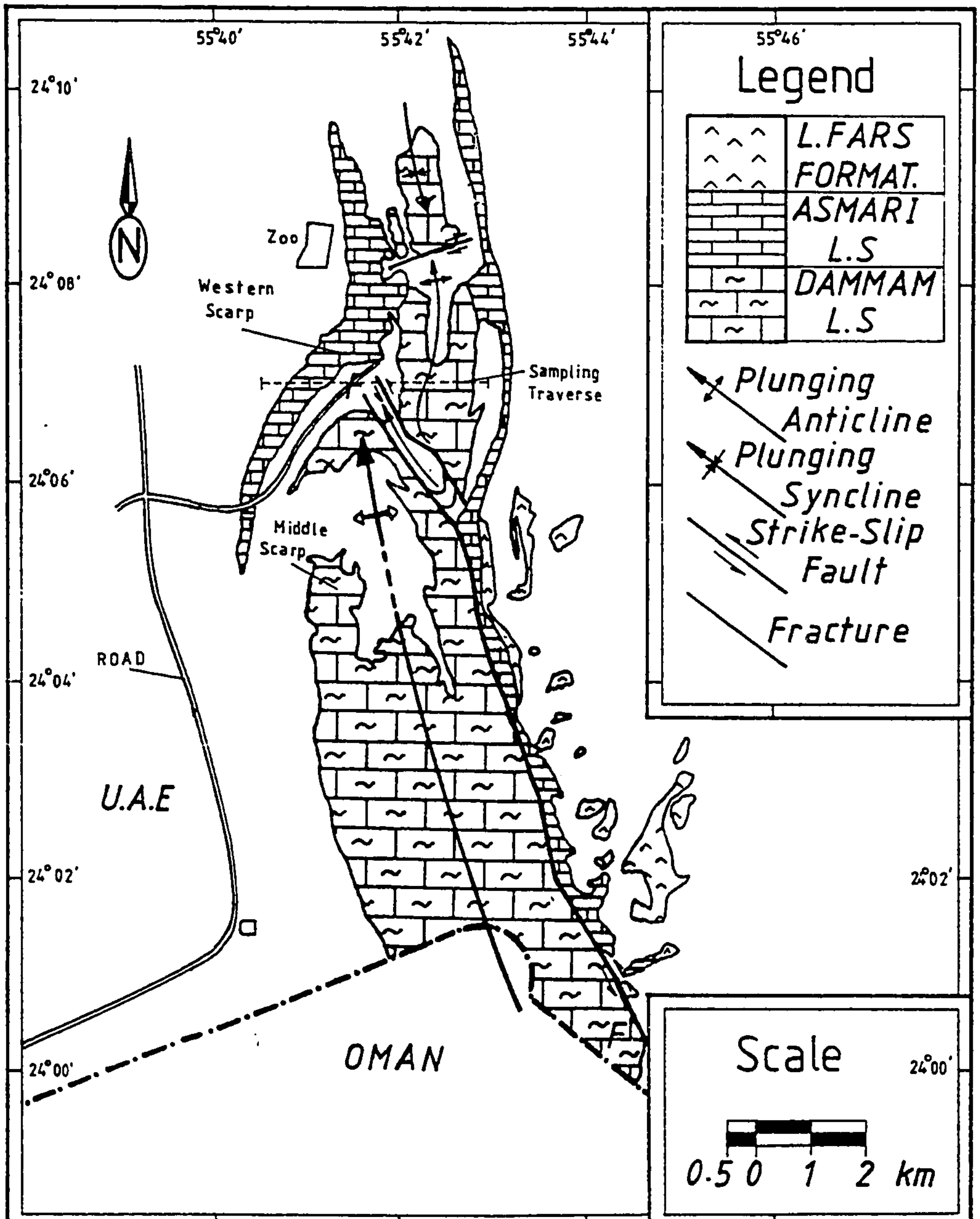


Fig.3 Geological Map Of Jabal Hafeet

(Modified after Cherif & El-Deeb,1984)

The main structural element in the area is the Hafeet anticline or Jabal Hafeet, a north-south trending, northerly plunging anticline exposing a succession about 400 m-thick of limy and marly rocks, in the closure of the fold. Jabal Hafeet is about 4.5 km wide and 25 km long, with about half of its length located in the U.A.E. and the other half extending into Oman. Despite the simple, broad structural outline of Jabal Hafeet, it is much more complicated on a smaller scale by several en-echelon folds and normal and strike slip faults as well as other structures. Some of these smaller structures were of syn-depositional nature and hence have greatly affected the pattern of sedimentation.

I.3 Materials and Method of analysis

The samples used in the present study (fig.3) were collected by Prof. El-Naggar during a field trip to the Jabal Hafeet area. They were collected from the exposed section in both the middle and the western escarpments of the northern part of Jabal Hafeet. No samples were collected from the lower part of the succession, simply because it is considered to be the lateral equivalent of the Middle Eocene Dammam Formation which has already been studied by several authors in many different parts of the Peninsula (e.g. El Nakhal, 1973; Tleel, 1973, Al Tamimi, 1985), while the collected section represents the only known outcrop of the Late Eocene (Bartonian) to Early Oligocene (Rupelian) succession in Arabia.

The sampling took place across the northern part of Jabal Hafeet along an east-west traverse (fig.3). The traverse includes two sections separated by the

Hafeet fault line, on which a paved road is constructed. The Late Eocene part of the succession is exposed in the core of the anticline on the eastern side of the road with *S* 35° *W* strike and 70° dip, while the Early Oligocene part crops out on the western side of the road, with *S* 5° *W* strike and 23° dip. The samples were collected on a 3-m interval basis, but due to the general uniformity of the lithologic composition of the succession, thin sectioned samples were taken every 6 m.

The methods used in the study of the thin sections included examination under a polarizing binocular microscope, exposing to an ultraviolet source (to differentiate between organic and non-organic matter) and photographing by the use of a photographic polarizing microscope. No staining techniques were attempted and the thin sections were found to contain an excellently preserved Nummulitid assemblage that was beautifully used for dating the succession.

1.4 Historical Review and Previous Work:

Oil and gas were discovered in commercial quantities in the Early Paleogene succession of the Saudi Arabia / Kuwait divided neutral zone, of the U.A.E., of offshore Iran, of northern Iraq and of Syria. Similarly commercial oil and gas deposits occur in the Late Paleogene-Neogene successions of both southwestern and offshore Iran, of both southern and northern Iraq and of Syria. However, the Late Paleogene succession (Late Eocene-Oligocene) is almost completely missing in most of Arabia except for its extreme southeastern parts (U.A.E., Omani desert and Dhofar). Consequently, no fossiliferous marine Late Eocene-Oligocene rocks are known in the Arabian sedimentary succession except for the subsurface of the U.A.E and in a small isolated outcrop at the western feet of the Oman Mountains known as Jabal Hafeet, and in Dhofar. Consequently, Jabal Hafeet became the focus of searching for fossiliferous marine Late Eocene-Oligocene rocks in Arabia.

Despite its wide spread development in both surface and subsurface sections all over eastern, northeastern and northern Arabia, and its importance as groundwater and hydrocarbon reservoirs, the Paleogene succession in this important part of the world has received very limited attention. Consequently, most of the Paleogene studies in the region are limited to oil companies and government reports. However, some information about the Paleogene succession in Arabia has been released, either in the form of completely published theses, papers drawn out from unpublished theses, projects or papers released by members of staff of different oil companies. These include: Henson (1950),

Steineke and others (1952, 1958), Sander (1962), Smout (1954), Thralls and Hasson (1956), Bramkamp and others (1958), Dunnington (1958), Owen and Nasr (1958), Aramco Staff (1958), James and Wynd (1965), Beydoun (1966), Powers and others (1966), El-Naqib (1967), Milton (1967), Willis (1967), Powers (1968), Tleel (1973), El-Khayal (1974b,c), Sugden (1975), Pinnington and others (1981), El-Naggar and others (1982), El-Naggar and Kamel (1988), El-Nakhal and El-Naggar (1989), Al-Furaih (1983), Cherif and El-Deeb (1983a,b, 1984), Hasson (1985), Naqash and others (1987) and Al-Sharhan (1989).
Some other publications that are mainly concerned with the tectonostratigraphic evolution of the Oman Mountains discussed the Paleogene succession in that particular area. These include: Glennie (1974), Ricateau and Riche (1980), Searle and others (1983, 1987), Clarke (1988), Nolan and others (1990), Boote and others (1990), etc. The Paleogene succession of Arabia was also included in some regional studies by Baker and Henson (1952), Law (1957), Kamen-Kaye (1970), Murris (1980).

Steineke and Bramkamp (1952) summarized the Mesozoic succession of eastern Saudi Arabia. Although their discussion was very brief, and was concerned mainly with the Jurassic succession and its oil content, they mentioned that the Late Cretaceous "Aruma Formation" is overlain by the "Umm Al Radhuma Formation", which they considered to be of Paleocene - Early Eocene age.

Smout (1954), studied "the lower Tertiary Foraminifera of the Qatar Peninsula" in both surface and subsurface sections, subdividing the succession into biozones, on the basis of its Rotaliid, Nummulitid and Alveolinid content. The succession was given a Paleocene - Middle Eocene age.

In a paper compiling the opinions derived from previously published articles by ARAMCO geologists Thralls and Hasson (1956), reviewed the history of exploration in Saudi Arabia and described the physiographic provinces, stratigraphy and structure of the eastern part of the Kingdom. Since their paper was lacking details, as explicitly admitted by them, the Paleogene succession in the producing area was only included as the "post-Cretaceous succession" with Paleocene to Middle Eocene age.

Steineke and Bramkamp (1958), defined the main sedimentary rock units used in Saudi Arabia, their intervening unconformities and the main structural elements of the area. Among other type and reference sections formally defined for the first time, the Paleogene succession was divided into three rock units from top to bottom as follows:

Top Dammam Formation.............(Middle Eocene)

Rus Formation......................(Early Eocene)

Bottom Umm Al Radhuma Formation......(Paleocene)

Dunnington (1958) discussed the generation, migration, accumulation and dissipation of oil in northern Iraq, where he summarized the tectonic framework, stratigraphic development and the oil fields in the region. He (*op.cit*) presented different isopach-facies maps, including one for the Paleocene-Lower Eocene, another for the Middle- Upper Eocene and a third one for the Oligocene successions.

Owen & Nasr (1958) studied the stratigraphy of the Kuwait-Basra Area based mainly on subsurface data collected from several oil wells. These authors (*op.cit.*) subdivided the Early Cretaceous - Pleistocene succession into several rock units (some of which were defined for the first time) and grouped the Paleogene succession in the region under the term "Hasa Group" { a term previously proposed by Sander (1952) in his unpublished Ph.D thesis as "the Hasa series"}. Owen & Nasr (*op.cit.*) defined reference sections for the different formations in the Kuwait- Basra area using the same terminology and age assignments already applied in Saudi Arabia, and hence considered the Hasa Group to be of Paleocene - Middle Eocene age.

Sander (1962) analysed the Paleogene succession in Eastern Saudi Arabia, by the use of its larger foraminiferid remains, introduced the term "Hasa Series" for the succession and discussed its regional variation as well as possible correlation with equivalent successions in both Egypt and India.

Both Powers and others (1966), and Powers (1968) studied the Paleogene succession in Saudi Arabia Among other stratigraphic units. In these two publications, the exploration history in the region, the main stratigraphic units, with its paleogeography, megastructural elements as well as tectonic framework have been discussed. Using previously suggested subdivisions and age assignments. Powers and others (1966) stated that " the extensive drilling throughout Saudi Arabia has failed to detect Upper Eocene or Oligocene strata", suspecting these rocks to occur in the Wadi Serhan basin in northwestern Saudi Arabia (the Hibr Formation) However, Powers (1968) restricted the age of the Hibr Formation to the Middle - Late Eocene age. Both publications agreed that the age of the Paleogene succession of central and eastern Saudi Arabia is of Paleogene-early Middle Eocene age, with some suspicion that their contact with the underlying Late Cretaceous Aruma Group could be disconformable.

Beydoun (1966) studied the geology of the eastern Aden protectorate and part of Dhofar, where he used the terms "Hadharamout Group" for the Early Paleogene and "Shiher" Group for the Late Paleogene successions in the region, respectively. He (*op.cit.*) subdivided the Hadharamout Group into four formations, ranging in age from Paleocene to Middle Eocene; but could not differentiate the second group because of the discontinuous and heterogeneous nature of its outcrops.

Al-Naqib (1967) reviewed the geology of southwestern Iraq, where the Early Paleogene succession was described to be well represented by four formations of Paleocene - Middle Eocene age, while the Late Eocene and Oligocene rocks are not recognized in that region, either due to erosion, nondeposition or both. Al Naqib (*op.cit.*) also mentioned that there is a major break between the Early Paleogene and the underlying Cretaceous rocks.

In a brief description for the surface and subsurface geology of Kuwait, Milton (1967) mentioned that the Late Paleogene succession (Oligocene) is exposed on the surface, while the earlier Paleocene - Middle Eocene age is recorded in the subsurface conformably overlying the Cretaceous succession.

Willis (1967) briefly studied the surface geology of Bahrain, mentioning that rocks as old as Early Eocene are partially exposed, while no Late Eocene or Oligocene rocks have been recognized.

Glennie (1974) studied the mountains of Oman with special emphasis on the mechanism and timing of emplacement of its ophiolite complex. Here, the Paleogene rocks were included in a sequence of mainly shallow marine "Maastrichtian and Early Tertiary carbonates" informally grouped under the term "unit F".

In an attempt to re-evaluate the depositional history, main structural elements, and oil productivity in the Arabian gulf region, Kamen-Kaye (1970) constructed a number of isopach maps for the sedimentary succession in the region, including the Paleogene. These, showed a sudden increase in the thickness of the succession from west to east, a phenomenon that was related to an abrupt transition from platform conditions to foredeep ones, and to another suspected foredeep along the Oman mountains.

El-Nakhal (1974) carried out a litho- and bio-stratigraphical analysis for the Late Cretaceous - Early Paleogene succession in Kuwait. This succession was considered to be of Paleocene - Middle Eocene age, with a probable disconformity between the Late Cretaceous and the Paleogene, and a regional break between the Paleogene and the Neogene that spans the Late Eocene - Oligocene time.

El-Khayal (1974 b, c) carried out a biostratigraphical study for the Early

Paleogene succession in the northwestern part of Saudi Arabia (the Hibr Formation), which he correlated with equivalent rock units in the eastern part of the country. An Early Paleocene age was given to the lower part of the succession in both regions, Early Middle Eocene age was assigned to the upper part of the Hibr rock unit and an Early Eocene age for the top of the Umm Al-Radhuma Formation in the East.

Sugden (1975) pointed out to the possibility of the presence of a break in sedimentation between the Late Cretaceous and the Paleogene successions in Qatar, considering the Late Paleogene period to be missing either due to uplift and erosion or non-deposition or both.

Murris (1980) discussed the tectonostratigraphic evolution of the Middle East basin and its hydrocarbon habitat, stating that the Late Eocene rocks are missing across the Arabian platform because of nondeposition, enhanced later, in the Early and Middle Oligocene, by a major drop in relative sea level.

Al-Furaih (1983) studied the Ostracoda of the Early Paleogene succession in a number of wells drilled in Eastern Saudi Arabia, and followed the previously suggested age assignment for this rock unit (Paleocene - Early Eocene).

Cherif and El-Deeb (1983 a, b,1984) studied the Paleogene succession of the Jabal Hafeet section (U.A.E) and considered it to be of Middle Eocene - Oligocene age on the basis of recorded planktonic and larger benthonic foraminiferid remains. A slight hiatus between the Late Eocene and the Early Oligocene beds in the succession was detected and was considered as an indication of a mild effect of the Pyrennean movement on the area. These authors (1984) subdivided the succession into several stratigraphical units and biostratigraphic zones, and presented an interpretation for the tectonic evolution of the area. Several minor unconformities were detected and were taken to account for the absence of Late Oligocene rocks in the succession. These were considered to be related to the effect of the Late Miocene (Helvetian) movements on the area.

Both of Kamel (1985) and Al-Tamimi (1985) studied some surface and subsurface Early Paleogene successions in Saudi Arabia. Kamel (1985) subdivided the Early Paleogene succession in the Turayf area, in northwestern Saudi Arabia into several litho- and biostratigraphic units and several microfacies. He assigned the succession, in that area to the Paleocene - Middle Eocene age. Similarly, Al-Tamimi (1985) subdivided the outcropping Early Paleogene succession in the Dammam Dome of eastern Saudi Arabia into several litho- and biostratigraphic units, as well as several microfacies, and dated the succession as of late Early Eocene - middle Middle Eocene age.

Hasson(1985) studied rock cuttings from 5 wells in the Rub'el Khali basin, Saudi Arabia, and on the basis of recorded planktonic foraminiferid remains, a period of non deposition or slow sedimentation at the base of the succession was taken to suggest the absence of most (if not all) of the Paleocene in eastern Saudi Arabia.

Naqash and others (1987) carried out a structural analysis for the Late Paleogene succession of Jabal Hafeet in the U.A.E., and related its deformation to the Alpine orogeny of Late Triassic - Holocene age.

In reviewing the exploration history in the U.A.E, Alsharahan (1989) summarized the main stratigraphic units, structural elements, hydrocarbon habitat, major reservoirs, seals and source rocks. The Paleogene succession in Abu Dhabi was included under the name "Hasa Group" (with its tripartite formations) while in Dubai and in the other northern Emirates, it was treated under its respective formational units. A period of uplifting and erosion was considered to have affected most of the Arabian Peninsula during the Late Eocene-Oligocene time, except in depressed areas such as Dubai, and parts of eastern Abu Dhabi, while in other northern Emirates, the Oligocene deposits could not be differentiated from the younger Miocene massive salts.

El-Nakhal and El-Naggar (1989) reviewed the biostratigraphy of the Early Paleogene succession in Saudi Arabia, Kuwait and the adjacent regions. They suggested that the age of the Early Paleogene succession in Arabia is of latest Paleocene - Middle Eocene age.

II.STRATIGRAPHICAL ANALYSIS

II.1 General Discussion

Despite being the shortest and the youngest Era, the Cenozoic witnessed one of the most important tectonic phases in the history of the Earth which is the compressive phase of the Alpine orogeny. This movement is considered to be -at least partly- responsible for the formation of the major hydrocarbon traps in the Middle East, particularly in Iran (*cf* Thomas, 1950; Kashfi, 1976; Murris, 1980) and in both Iraq and Turkey (Baker and Henson, 1952; Pomerol, 1982), as well as through the Arabian gulf basin (*cf.* Beydoun, 1988)

The Cenozoic Era also witnessed great global climatic changes such as a the Plio - Pleistocene glaciations, periods of humidity followed by periods of aridity and marked fluctuations in the sea level. These changes, which were attributed to the polar wondering, together with the syn-depositional tectonic activities played a great role in the formation of the source - reservoir - seal tried in the Middle East.

The Cenozoic Era began at about 65 Ma, and has been subdivided into several periods by several authors as follows:

1- Brongniart (1810) and Desnoyers (1829) introduced the terms Tertiary and Quaternary, respectively, as the two major subdivisions of the Cenozoic Era. These were used in corollary with the terms "Primary" and the "Secondary", which had already been used by different workers to mean different things. Some authors used the term "Primary" to mean the Pre-Cambrian, while others used it to mean the Paleozoic. Similarly, while some authors used the term "Secondary" to mean the Mesozoic, others used it for most of the Phanerozoic eon. Consequently, the usage of the terms Primary and Secondary has been stopped but the misusage of the terms "Tertiary" and "Quaternary", although condemned by the International Geological Congress, and rejected by El Naggar (1969), have continued to be used in the geological literatures with many different definitions.

2- Furthermore, both Hoernes (1853) and Naumann (1866) subdivided the Tertiary into Paleogene and Neogene while others extended the Neogene to include the Quaternary or only equated it with the later. Some authors even raised both the Tertiary and the Quaternary to the status of an era, and both the Paleogene and the Neogene as well as the Pleistocene and Holocene to the status of a system. Others used the subdivision Paleogene, Neogene and Quaternary with different meanings (*cf.* Gignoux, 1955). However, it has been the practice by a good many geologists today to use a Tertiary System (with the Paleocene, Eocene and Oligocene series) and Quaternary System (with the Miocene, Pliocene, Pleistocene and Holocene series).

3- El-Naggar and Dawood (1979) proposed a subdivision for the Cenozoic Era into three periods:- The Paleogene {adopted after Naumann, 1866, and includes three epochs: the Paleocene of Schimper, 1874, the Eocene of Lyell, 1833 and the Oligocene of Beyrich, 1854}; The Mesogene (which includes two epochs: the Miocene and the Pliocene both of Lyell, 1833) and the Cainogene (which covers the rest of the Cenozoic era and includes two epochs: the Pliocene of Lyell, 1839 and the Holocene of Gervais, 1867). This classification is followed here.

II.2 The Paleogene Period:-

The Paleogene period is the longest period in the Cenozoic era (40 m.y. from 65 Ma to 25 Ma). It was introduced by Naumann (1866) to unite the then only two epochs, the Eocene and the Oligocene. Later, Schimper (1874) included the earlier part of the Eocene into a separate epoch which he named the Paleocene. The Paleogene was considered to be synonymous with the term Nummulitic previously introduced by d'Archiac and Haime (1853). however, a later definition to the Nummulitic by both Renevier (1896) and Haug (1907) proved that the two terms are not synonymous. Although, the limits and the subdivisions of the Paleogene are still the subject of much discussion (Pomerol, 1982), it is considered to include the Paleocene (12 m.y. from 65 Ma to 53 Ma), the Eocene (17 m.y. from 53 Ma to 36 Ma and the Oligocene (13.5 m.y. from 36 Ma to 22.5 Ma).

II.2.1 The Paleocene Epoch:

According to El-Naggar (personal comm.) the Paleogene Period (particularly in Arabia) can be subdivided into an Early Paleogene, which includes both the Paleocene and the Middle Eocene and a Late Paleogene which extends to the end of the Oligocene, being usually separated by a marked post-Middle Eocene break.

Since the age of the section studied here, is of Late Paleogene age, the following discussion will be concentrated on this interval. A detailed discussion to the stratigraphy of the Paleogene Period can be found in many previous writings by El-Naggar (1966, 1967a, 1967b, 1969, 1979) and by a large number of his students including El-Nakhal (1973), Al-Tamimi (1985), Kamel (1985) and Wasimuddin (1985). Meanwhile, a brief discussion to the Eocene and Oligocene epochs was deemed necessary, since publications on the Late Paleogene succession in Arabia are very much limited.

II.2.2 The Eocene Epoch:-

This Epoch, introduced by Lyell (1833) is considered here to represent the period between 58 Ma and 36.6 Ma and to include the following ages:-

1) The Early Eocene age comprising the Ypresian stage (defined by Dumont, 1849 after the Ypres clay of Belgium) with a duration form 57.8 Ma to 52 Ma.

2) The Middle Eocene age comprising the Lutetian stage (defined by De Lapparent, 1883 after Lutece = Paris) with a duration form 52 Ma to 41.3 Ma.

3) The Late Eocene age comprising both the Bartonian stage (defined by Mayer-Eymar, 1857, after the Barton Cliff in Hampshire, England.) with a duration from 41.3 Ma to 38 Ma and the Priabonian stage (defined by Munier-Chalmas & De Lapparent, 1893 after pria bona = good stone in the Venetian dialect) with the duration from 38 Ma to 36.6 Ma.

II.2.3 The Oligocene Epoch:-

This epoch was defined by Beyrich (1854) to unite the formations between the Late Eocene and the Early Miocene both defined by Lyell (1833). The Oligocene in the present study will be considered to represent the period between 36.6 Ma and 24.4 Ma and to include the following stages:-

1) The Early Oligocene age which comprise the Rupelian stage (defined by Dumont, 1849, after the Rupel, a tributary of the river Scheldt in Belgium) with a duration from 36.6 Ma to 32.7 Ma.

2) The Late Oligocene age which comprises the Chattian stage (defined by Fuchs, 1894 after the ancient tribe Chattian which lived in the Cassel region, western Germany) with a duration from 32.7 Ma to 24.4 Ma.

II.3 The Early Paleogene rocks in Arabia:

The Early Paleogene succession of Arabia (fig.1) is separated from the underlying Late Cretaceous succession by a major unconformity. The nature and duration of such unconformity were a matter of debate among many authors. It was considered to be conformable by many earlier authors (e.g Sander, 1962) or only locally unconformable in elevated areas (e.g Henson, 1955; Powers and others, 1966), or to be a regional hiatus with varying durations {Danian-Montian (e.g Page, 1959); Danian (e.g Smout, 1959); Danian-Heersian (e.g El-Nakhal, 1973)}. Some other authors mentioned the presence of the hiatus without giving any duration (e.g Steineke and others, 1958). However, Hasson (1983,1985) has recently identified an Early Eocene planktonic assemblage (belonging to the *Globorotalia formosa*) Zone in shaly horizons near the base of the subsurface Umm Al Radhuma Formation in the Rub' Al Khali Basin. Hence, the age of this Formation was considered to be Early Eocene, with the possibility that the short column of sediments between the Early Eocene planktonic shaly horizon and the top of the underlying Aruma Group could be assigned to the Late Paleocene. However, there is no criteria to date the sparse benthic Foraminifera that lie below the planktonic foraminiferal zone.

After the Late Cretaceous uplift and erosion, the Paleogene in Arabia commenced with a transgressive phase that covered the Arabian plate almost entirely during at least the Late Paleocene - Middle Eocene time. This transgression resulted in the deposition of a widespread, thick, calcareous succession which is collectively included under the name Hasa Group. This group comprises three basic formations which are known from base upward as the Umm Al Radhuma, Rus (or Umm Al-Ruaus) and the Dammam Formations.

The Umm Al-Radhuma Formation is represented in Saudi Arabia by a repetitious succession (about 243 m thick) of foraminiferal, micritic and calcarenitic limestones and dolomites, with some local silicification (fig.1). It is considered to be of Late Paleocene - Early Eocene age (Steincke and others, 1952,1958; Powers and others, 1966; Powers, 1968).

Similar rocks are included under the same name of Umm Al-Radhuma in Qatar (Sugden and Standring, 1975) and in both southern Iraq and Kuwait (Owen and Nasr, 1958; Al-Naqib, 1967; El-Nakhal and El-Naggar, 1989). The locations of both the type and reference sections for this rock unit are indicated (figs.1,4,5).

In both Interior Oman and northern Yemen, the Umm Al-Radhuma Formation is represented by dolomitic limestones with minor argillaceous intercalations (Beydoun and Greenwood, 1968; Beydoun, 1988; Clarke, 1988) but in southern Yemen, the Early Eocene part of the succession was treated separately under the name Jiza' Formation while the Paleocene part was included under the name Umm Al-Radhuma Formation (Beydoun, 1966). However, these change laterally into basinal shales and argillaceous limestones in the subsurface of offshore Abu Dhabi (Al-Sharhan, 1989), and into still more deeper basinal shales and marls in the subsurface of both offshore Dubai

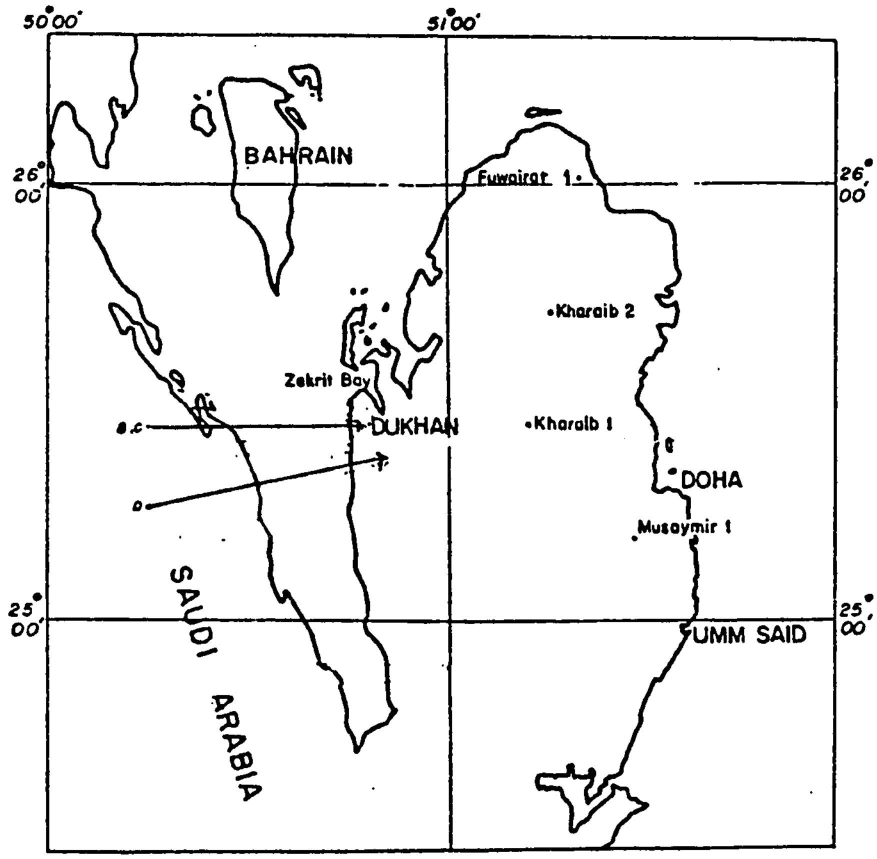


Fig.4 : An index map showing the locations of the different Paleogene reference sections in Qatar (From Sugden & Standring, 1975).

Reference Sections.

B. Dammam Formation.
C. Rus Formation.
D. Umm er Radhuma Formation.

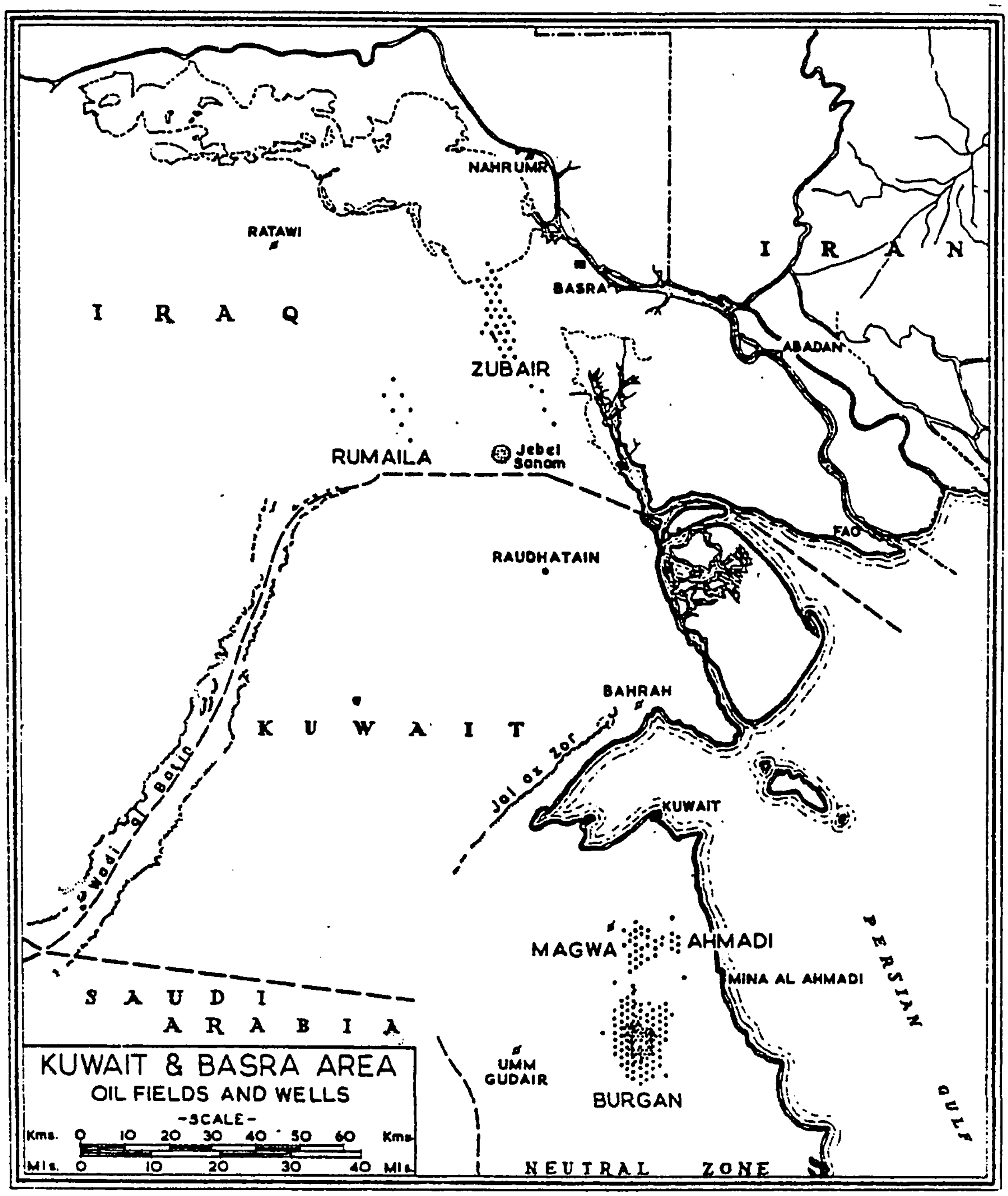


Fig.5 : An index map showing the locations of both Burgan and Zubair fields in the Kuwait and Basra areas. The reference section for the Paleogene succession in Kuwait was chosen in the Burgan # 10 well, while the Zubair # 3 well was chosen as a reference section in southern Iraq (From Owen & Nasr, 1958).

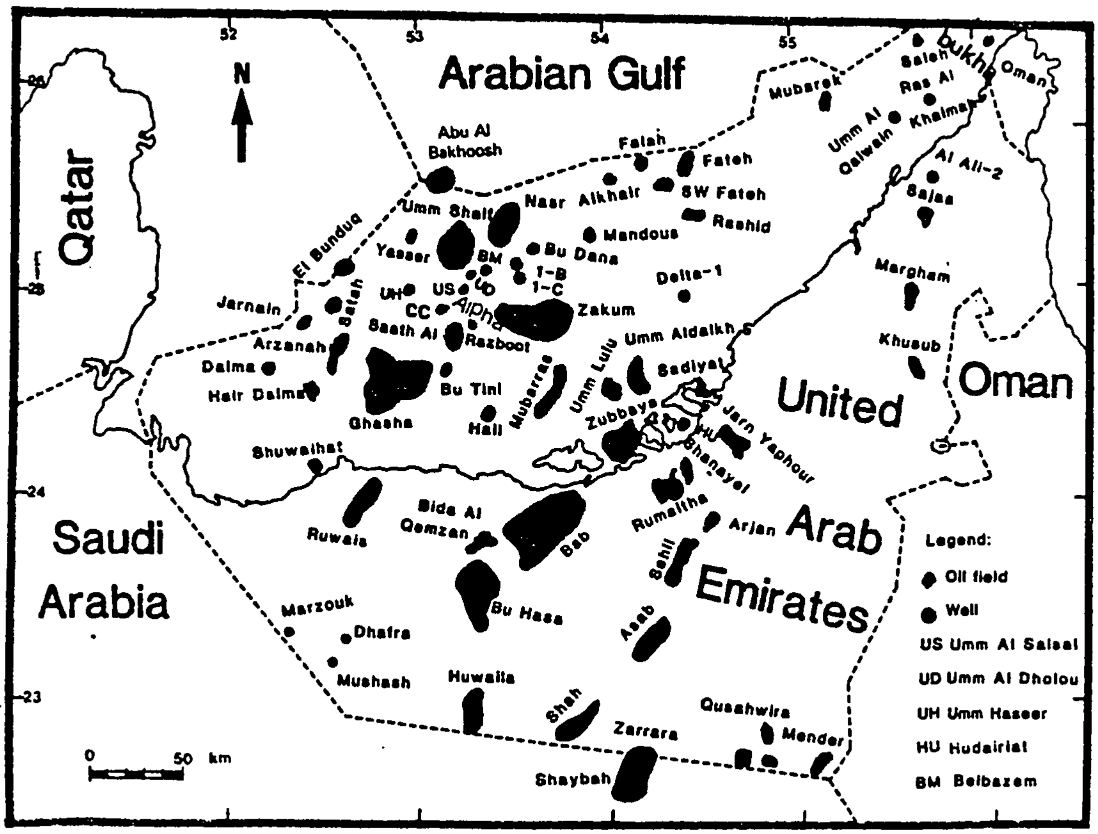


Fig.6 : A location map for the major oil fields in the U.A.E., where the reference sections for the Paleogene succession have been chosen (From Al-Sharhan, 1989).

(Pinnington, 1981) and western Iran (James and Wynd, 1965). These basinal facies have been included under the Pabdeh Formation while the equivalent shallower facies in western Abu Dhabi are still included under the name Umm Al-Radhuma (Al-Sharhan, 1989). Locations of the reference sections for this rock unit are indicated (fig.6).

In the Oman Mountains proper, the Paleocene - Early Eocene rocks were deposited along the flanks of the already risen structure and are represented by the shallow carbonate Jafnayn Formation (fig.1) except in both the Northwest, where it is represented by parts of the mixed basinal and turbiditic facies of the Muthaymimah Formation (fig.1), and in the North-Northeast, where it is represented by parts of the basinal Ruwaydah Formation (*cf.* Nolan and others, 1990).

The Umm Al Radhuma Formation is followed in Saudi Arabia by a succession of chalky limestones, marls, dolomitic limestones and dolomites, (about 56 m thick) that was considered to be of Early Eocene age and was included under the name "Rus Formation". The contacts of the Formation with both the underlying Umm Al-Radhuma and the overlying Dammam Formations were described as conformable (Powers and others, 1966 Powers, 1968). The formation was described to be limited in outcrop to two small areas, the first of which is a narrow band extending some 180 km northward from Wadi Al Sahba and the second is a nearly circular patch about 10 km in diameter cropping out in the breached core of the Dammam Dome. However, the formation was described as widespread in the subsurface of the Eastern

Province, the Rub'al Khali and the Arabian Gulf. The Formation was described to vary in thickness from less than 30 m in the Ghawar field wells to more than 150 m at Abu Hadriyah and up to 255 m in the Rub'al Khali.

Al-Tamimi (1985) subdivided the Rus Formation in Eastern Saudi Arabia into two members from base to top as follows:

1- The Aqrabiyah Chalk Member.

2- The Dhahran Dolomite Member.

He (*op.cit.*) proved that the upper Member of the Rus Formation is of Early Lutetian age on the basis of a rich assemblage of planktonic foraminifera.

In Kuwait, the Rus Formation (fig.5) is represented by dense anhydrite with chalky limestones and minor dolomite interbeds as well as traces of shales and marls (76 m thick). Its contacts with both the overlying and the underlying units were described as conformable. Its age was interpreted as Middle Eocene (Owen and Nasr, 1958).

In southwestern Iraq, the Rus Formation is represented by a succession of massive, crystalline anhydrite with calcareous intercalations and thin shaly and marly interbeds (about 94 m thick). The upper boundary of the formation was described to be generally conformable, but with local unconformities (Owen and Nasr, 1959) or unconformable with local conformities (Van Bellen, 1958, Al-Naqib, 1967). Its age was also interpreted differently by many authors e.g Middle Eocene by Owen and Nasr (1958) or Early to Middle Eocene by Van Bellen and others (1958). The location of the Rus reference section is indicated (fig.5).

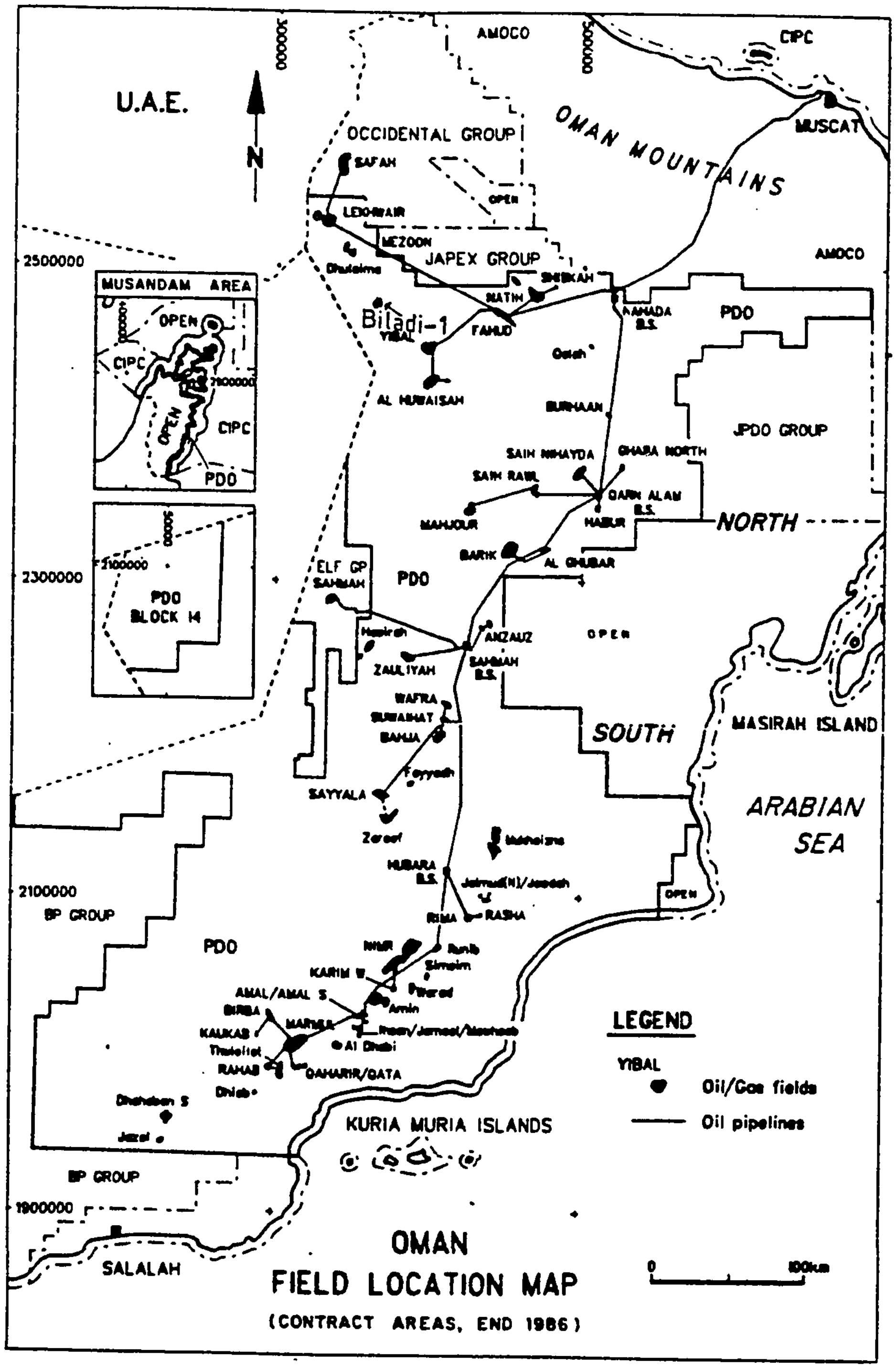


Fig.7 : An index map for the major oil fields in Interior Oman, showing the location of Biladi-1 well where the reference section for the Paleogene succession in Oman has been taken (After Clarke, 1988).

The Formation thins drastically in Qatar to only 36 m at the Jabal Dukhan section (fig.4), being represented by dolomitic chalk with occasional calcarenite beds and chert nodules. Its contacts were described as conformable and its age was interpreted as Early Eocene (Sugden and Standring, 1975).

The Rus Formation in Interior Oman (Dhofar) is represented by an evaporitic succession of gypsum and anhydrite with some dolomite and dolomitic marl (130 m thick) with conformable boundaries and an interpreted Early Eocene age. A reference section was chosen in the succession penetrated by the Biladi-1 well (fig.7). This formations was included as part of the Hadhramaut Group (Clarke, 1988).

In Yemen, the Rus Formation is represented by a succession (138 m thick) of gypsiferous to chalky limestones interbedded with massive gypsum. Both its lower boundary (with the underlaying Umm Al Radhuma Formation) and its upper boundary (with the Habshiyah Formation) were described as conformable and gradational and its age was interpreted as Early Eocene (Beydoun, 1964).

In offshore Abu Dhabi, the Rus Formation is represented by an evaporitic succession (about 100 m thick), being mainly composed of alternating anhydrite and dolomite beds with some argillaceous limestones at the base. Both boundaries were described as conformable and the succession was given an Early Eocene age (ADMA report, 1985).

The facies changes laterally in both offshore Dubai and western Iran into a very thick succession of argillaceous limestones that represent both the Umm Al

Radhuma and the Rus Formations and is generally included under the name "Pabdeh Formation". The thickness of this formation is recorded to be of more than 300 m in the subsurface of offshore Dubai (Pinnington, 1981) and to be more than 800 m in the subsurface of offshore Iran (James and Wynd, 1965). The upper boundary of the Pabdeh Formation with the overlaying Dammam Limestone was described to be conformable, while its lower boundary with the underlaying Late Cretaceous rocks is described as a considerable hiatus. The age of the Pabdeh Formation was interpreted as Paleocene - Early Eocene.

In northern and Central Oman Mountains, the Early Paleogene succession is highly complicated. Hence new rock unit names have been used to describe the succession (fig.2) where the Rus equivalents are included under the Rusayl Formation and parts of the Seeb Formation. The former rock unit is represented by variegated shales and marls with occasional thin chalky bands followed upwards by chalky limestone and minor sandy interbeds. Its lower boundary was described as disconformable while its upper one as apparently conformable with the Seeb Formation and its age was interpreted as Early Eocene.

The overlaying Seeb Formation (with the lower part of which the Rusayl Formation interdigitates) is represented by a sequence (56 m thick) of bioturbated, nodular calcarenites with a middle marly limestone horizon. Its lower boundary was described as conformable while its top was said to be unexposed. The age of the Seeb Formation was interpreted as Middle Eocene (Montenat and Blondeau, 1977) and the unit was correlated by Nolan and others (1990) with the Dammam Formation, but the lower part of it may well represent the upper part of the Rus Formation.

The upper unit in the Hasa Group is the Dammam Formation. This formation is represented in Saudi Arabia by a reduced succession (about 32 m thick) of shales, marls and limestones that constitute the Dammam Dome and crops out in a narrow irregular band from Wadi Al Sahba northward for a distance of about 180 km (fig.1). The band has a width of less than 5 km and has a somewhat discontinuous escarpment on the west. A relatively large exposure of the Dammam Limestone occurs at the base of Qatar Peninsula and a numerous isolated exposures constitute the eastern and southeastern margins of the Rub'al Khali Basin. The Dammam Formation is widely represented in the subsurface where it thickens drastically, extending over most of eastern, northeastern and southeastern Arabia, including large parts of the Rub'al Khali.

The type Dammam was subdivided from the base upward into the Midra Shale Member, the Saila Shale Member, the *Alveolina* Shale Member, the Khobar Member and the Alat Member. But these were lumped by Al Tamimi (1985) into three members only from the base upward as follows:- the Midra Shale Member (including both Midra and Saila), the Khobar Limestone Member (including at its base the *Alveolina* Limestone Member) and the Alat Limestone Member. The formation was considered to be of Early-Middle Eocene age (Powers, and others, 1966, Powers 1968) but it was proved by Al Tamimi (1985) to be of Middle Eocene age. The lower boundary of the Dammam Formation was described to be conformable while its upper boundary is truncated by the post - Dammam unconformity.

The Dammam Formation is represented in Kuwait by a much thicker section (178m) of chalky, dolomitic limestones, interbedded with marls and grading upward into dolomites and anhydrites. It thickens more in the subsurface of southwestern Iraq where it reaches a thickness of 225 m, being represented by similar facies, stratigraphic position and boundary relationships (Owen and Nasr, 1958; Al Naqib, 1967). However, it thins out in Qatar to only 52 m with similar facies, stratigraphic and boundaries relationships.

The Dammam Formation remains persistent in the subsurface of offshore Abu Dhabi, where it is represented by a succession (235 m thick) of marls and argillaceous limestones that passes upwards into packstones - grainstones, ending with tidal flat dolomites. The succession here becomes gradually more complete towards the east, and hence it is of Middle Eocene age in the western part of offshore Abu Dhabi, but of Middle-Late Eocene age in the eastern part. Its lower contact is conformable throughout, while its upper contact with the overlying Asmari Limestone is unconformable in onshore Abu Dhabi (Pinnington, 1981) becoming gradually conformable offshore (ADMA report, 1985).

The Dammam Formation thickens to 489 m in the subsurface of offshore Dubai, where it is represented by dolomitic limestone with anhydritic streaks at the base, passing laterally into marly and shaly facies in more basinal areas towards the North and the East. Consequently the section becomes gradually more complete and represents the Middle-Late Eocene age (Pinnington 1981).

In Interior Oman (Dhofar), the Dammam Formation remains persistent, being represented by slightly dolomitized limestones, with minor marly interbeds (142 m thick). It has the same stratigraphic position, lithology, fossil content and boundary relationships. Its age is interpreted as Middle Eocene with possible extension to the Late Eocene in the extreme northern part of Oman (Clarke, 1988). A more argillaceous lateral equivalent of the uppermost members of the Dammam Formation (fig.8) have been included under the name Andhur Formation (Clarke, 1988).

In southern Yemen, Dammam equivalents are included under the name Habshiyah Formation which is represented by shales and chalky gypsiferous, dolomitic limestones (224 m thick) with similar stratigraphic position and boundary relationships as well as an interpreted age of Middle Eocene. Here the post-Dammam unconformity is also remarkable, representing a regional hiatus.

In central and northern Oman Mountains, the Seeb Formation is considered to be the lateral equivalent of the Dammam Limestone. However, it is represented by a much thicker section (356 m) of bioturbated, nodular calcarenite with marly limestone interbeds and abundant nummulitic and alveolinid remains. Its lower boundary was described as probably disconformable with the underlaying Jafnayn Formation while its top was described as unexposed. The age of the Seeb Formation was interpreted as Middle Eocene (Nolan and others , 1990) which confirms its equivalency with the Dammam Limestone. Other units introduced for the Omani Paleogene succession in the highly disturbed areas, such as the Muthaymimah (turbiditic

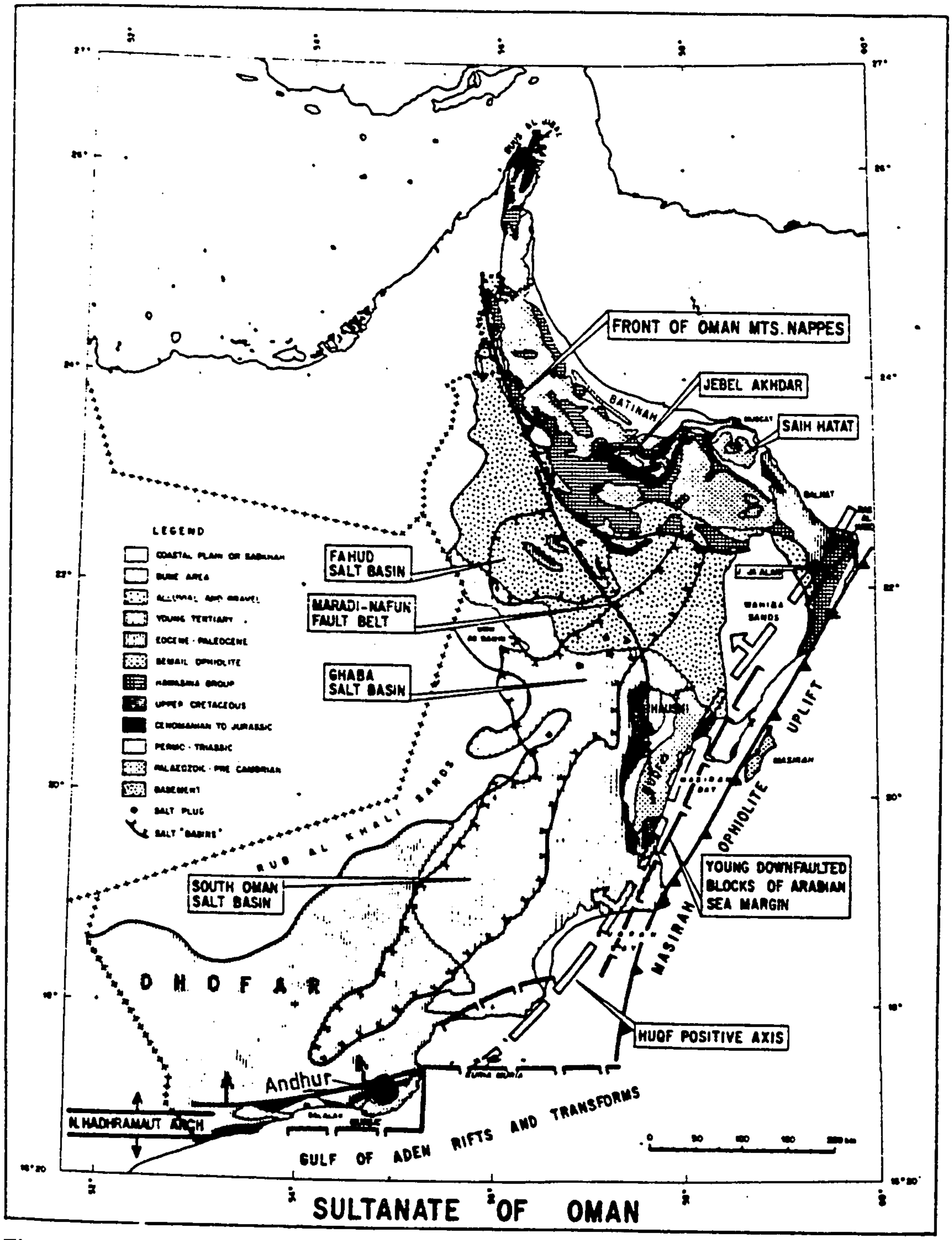


Fig.8 : An index map showing the location of the Middle Eocene Andhur type locality in Dhofar (After Clarke, 1988).

facies) and the Ruwaydah (basinal facies) Formations could not be directly correlated with members of the Hasa Group (Nolan and others, 1990).

II.4 The Late Paleogene Rocks in Arabia:

No fossiliferous marine Late Eocene-Oligocene rocks have yet been recorded in either Saudi Arabia, southern Iraq, Kuwait or Qatar (Thralls and Hasson, 1956; Owen and Nasr, 1958, Steineke and others 1958; Page, 1959; Powers and others, 1966; Al Naqib, 1967, Milton, 1967; Powers, 1968; Tleel, 1973; Sugden and Standring, 1975; Murris, 1980; Hancock and others, 1987; Beydoun, 1988 and El-Nakhal & El-Naggar, 1989).

These rocks are only found in a small embayment on the extreme eastern and southeastern margins of the Arabian plate, apparently extending from western Iran to the central part of the Omani Desert. The absence of fossiliferous marine Late Eocene - Oligocene rocks across the rest of the Arabian plate could be explained by non deposition over the gradually prograding Middle Eocene carbonate platform, which is one of the accepted hypotheses (*cf.* Murris, 1980). However, deposition followed by regional uplifting and subsequent erosion can not be excluded at least in part (*cf.* Powers, 1968; Pinnington, 1980; Beydoun, 1988; Al-Sharhan, 1989). The latter assumption is supported by a number of evidences that indicate the reactivation of the positive megastructures during the Late Eocene - Oligocene time. Such reactivation was associated with the initial phase of collision between the Arabian and the Iranian plates. Indeed, Beydoun (1988) mentioned that the Hadhramaut Arch had intermittently been positive at various times since the Paleozoic , and during the Late Eocene, it emerged with the general uplift of the region. Similarly, Pinnington (1980) mentioned that the Late Eocene uplift was most effective in Qatar, as the Qatar Arch had always been one of the major positive elements in the region. A similar phase of uplift was mentioned by Koop and Stoneley (1982) in the Zagros basin, where reactivation of the ancestral inner Zagros mountain area during the Late Eocene - Oligocene time had resulted in the shifting of the axis of the basin of deposition towards Arabia.

Consequently, the marine Late Eocene - Oligocene sedimentation was confined to an elongated, narrow embayment extending from Syria, northern Iraq and western Iran, into the U.A.E., and the Omani Desert.

Another event that is believed to have also affected the distribution of the Late Eocene-Oligocene sediments in the region, is the remarkable drop in the sea level during the Late Oligocene (Chattian) time (*cf.* Vail and others, 1977; Haq and others, 1987). This could have resulted in the erosion of any previously deposited Late Eocene - early Oligocene sequence over the eastern parts of the Arabian plate. The restriction of the Oligocene, deep water, marly facies to the middle part of the Omani foreland basin, and the shallower, neritic carbonates along the periphery of the basin can be be taken to support the deposition of the Late Eocene - Oligocene sediments in that basin only.

Other evidence that the region was affected by the Late Oligocene low sea stand can be found in many deltaic deposits in the region, such as of the deltaic Ahwaz Sandstone Member of Iran, which is considered to be the wedge edge of the Ghar Formation of both Kuwait and southeastern Iraq (*cf.* James and Wynd, 1965). The encroachment of deltas over carbonate platforms is usually noticed during the relative drops in the sea level. (Kendall and Schlager, 1980).

The Late Paleogene rocks in Arabia are represented by both the upper part of the Dammam *s.l.* Formation (of Late Eocene age) and the Oligocene part of the Asmari Formation. The upper part of the Dammam *s.l.* Formation is represented by glauconitic, peloidal, nummulitic limestone while the lower part of the Asmari Formation is represented by reefal limestone with minor shaly intercalations at the base. In the eastern part of offshore Abu Dhabi, the Asmari facies changes into bioclastic limestones and shales with apparent conformable relationship (ADMA report, 1985).

In Khuzistan (southwestern Iran), the Asmari type section is represented by a thick sequence of limestones with shelly intercalations. It overlies conformably the Pabdeh Formation and is conformably followed by the Miocene Gachsaran Formation.

In southwestern Iran, the Asmari Formation grades downwards into the marls of the Pabdeh Formation and is divided by James and Wynd (1965) into three informal members as follows:-

1- The Lower Asmari of Oligocene age (Rupelian to Chattian).

2- The Middle Asmari of Early Miocene age.

3- The Upper Asmari of Early Miocene age.

The rich nummulitic, Lepidocycline limestone facies of the Lower Asmari is not present in the type section but is well developed at the Gachsaran oil field, southern Khuzestan. The Oligocene fossil assemblage of the Lower Asmari was described by Thomas (1950) to include the following microfouna: *Nummulites intermedius* d'Archiac, *N. vascus* Joly and Leymeric, *Fusarchaias operculiniformis* (Henson), *Peneroplis thomasi* Henson, *Praerhapydionina delicata* Henson. This same assemblage of microfossils has been recorded in the Early Oligocene part of the Jabal Hafeet section as will be discussed later.

Correlation of the Paleogene succession in Arabia (Appendix B) with the studied section (figs.9,10) clearly illustrates the persistence of the post-Dammam unconformity with its varying magnitude across Arabia. It also demonstrates the complete absence of the Late Eocene - Early Oligocene succession throughout the Peninsula, except for the subsurface of the U.A.E. and the single surface section of Jabal Hafeet. Again, correlation with the internationally accepted Planktonic Foraminiferid and Nummulitic biozones (fig.9) proves the magnitude of this break to span the Brtonian - Burdigalian times, reaching its climax in Qatar, and dying out gradually towards the subsurface of the U.A.E. Figure (10) shows that the Paleogene succession thins out gradually towards both the northern and the southern parts of Arabia, while to the east of central Arabia, a thicker succession of a relatively deeper water nature was deposited, reflecting the localized, relative subsidence of this particular area during the Late Paleogene time.

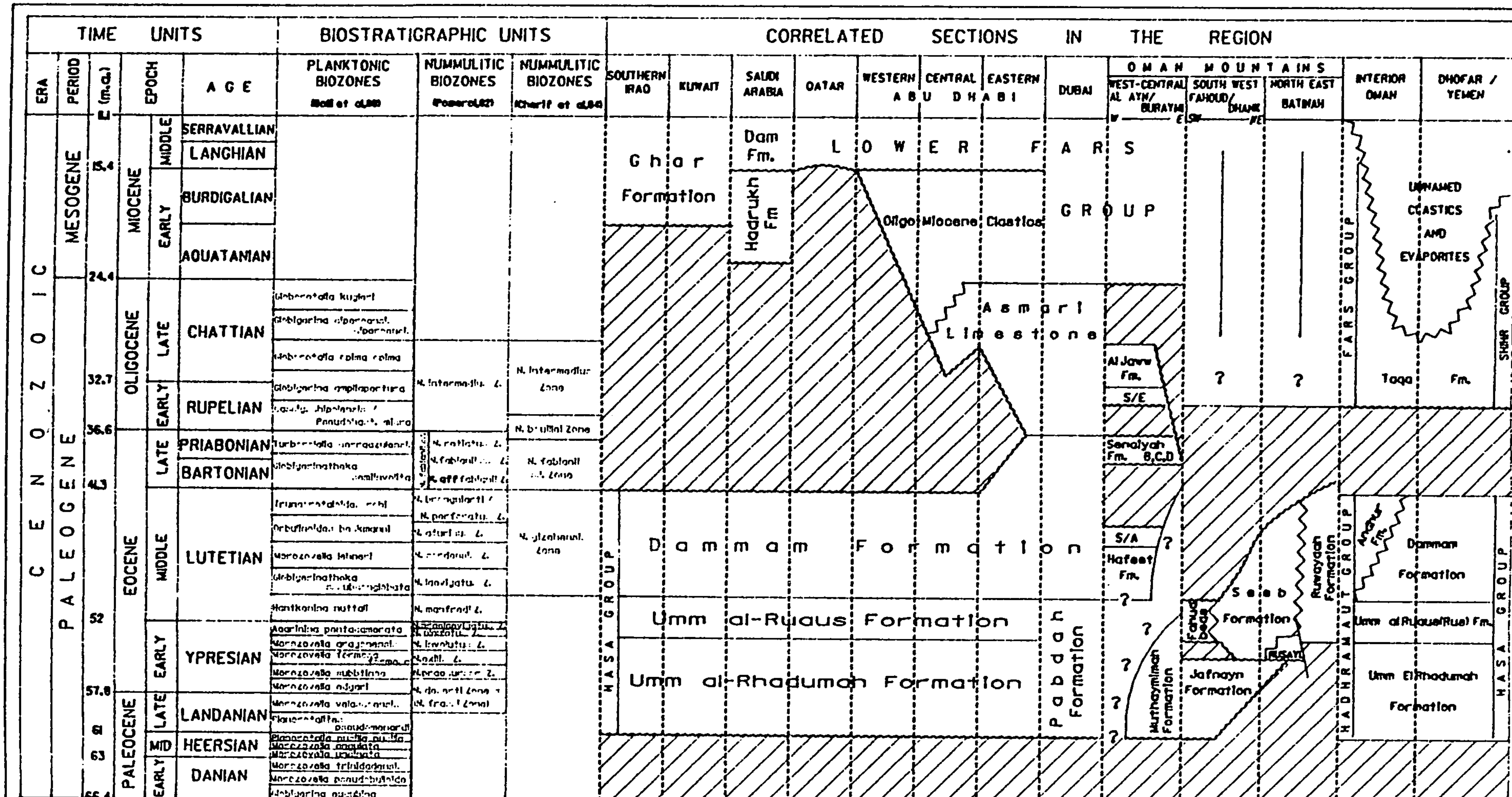


Fig.(1) : Corelation Chart For the Paleogene Succession In Arabia

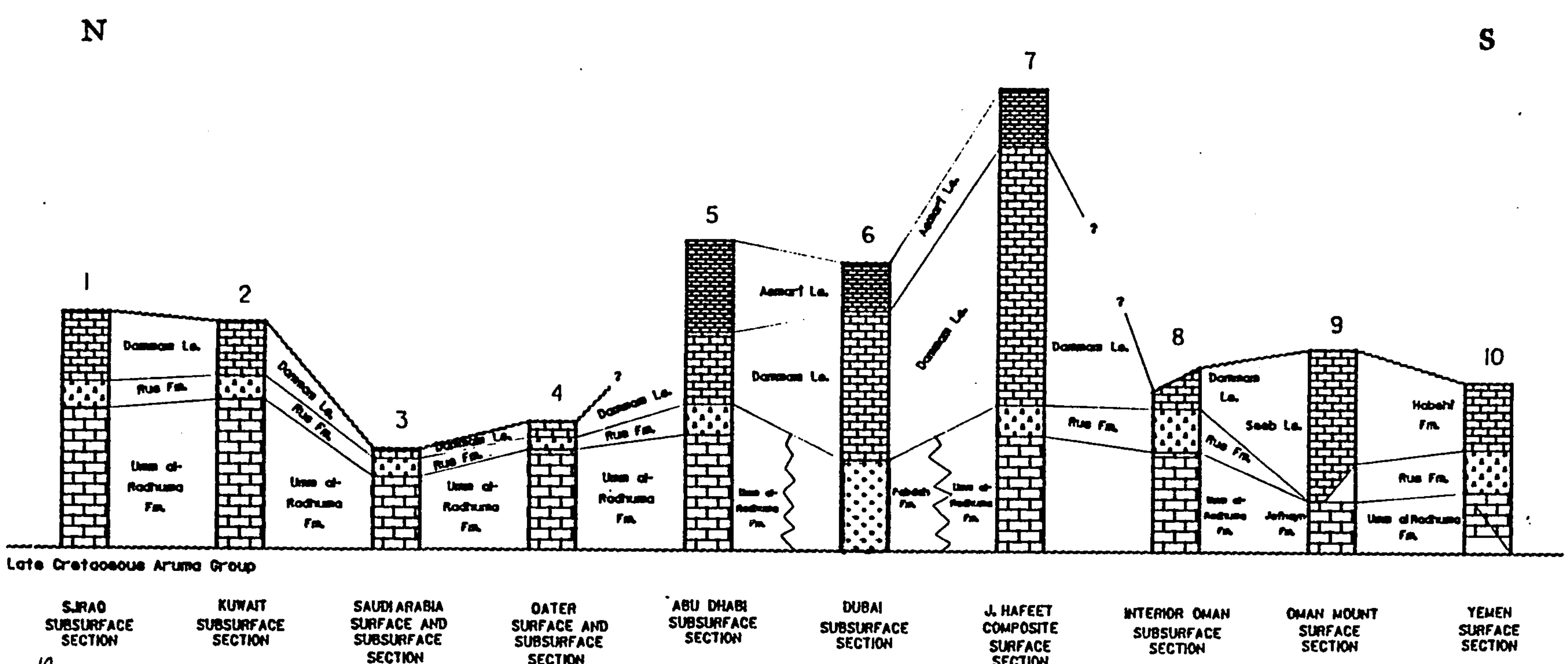


FIG.10 : ~~CORRELATION~~ FOR THE STUDIED PALEOGENE SURFACE AND SUBSURFACE SECTIONS OF EASTERN ARABIA

II.5 Lithostratigraphic Analysis of the Late Paleogene succession of Jabal Hafeet:

The Jabal Hafeet area did not attract the attention of many geologists until 1979 when Hunting Geol. and Geop. LTD. constructed a geological map for the area and subdivided the sedimentary sequence into several informal units. The results of this work was confined to governmental reports and has not yet been published. Cherif and El-Deeb (1984) studied the Al Ayn area, and revised its lithostratigraphical succession, introducing a number of new rock names (fig.11), and establishing several biostratigraphical units. According to these authors (*op.cit*). The sedimentary sequence was subdivided into the following units which were introduced as new.

Top Al-Jaww Formation (Middle Oligocene)

Senayciah Formation (Late Eocene - Early Oligocene)

Bottom Hafeet Formation (Middle Eocene)

Cherif & El-Deeb (*op.cit.*) further subdivided both the Hafeet and the Senayciah Formations into several members, that have not been formally named. These members were only given alphabetic or lower and upper designations and hence are here dropped, being of informal nature. Article 30(e), of the North American Stratigraphic Code (1983), states that "..Members designated solely by lithic character (for example, siliceous shale member), by position (upper, lower), or by letter or number, are informal.". According to the present study, the names Hafeet, Senayciah and Al-Jaww were found to be of a very localized nature and hence do not contribute to regional correlation.

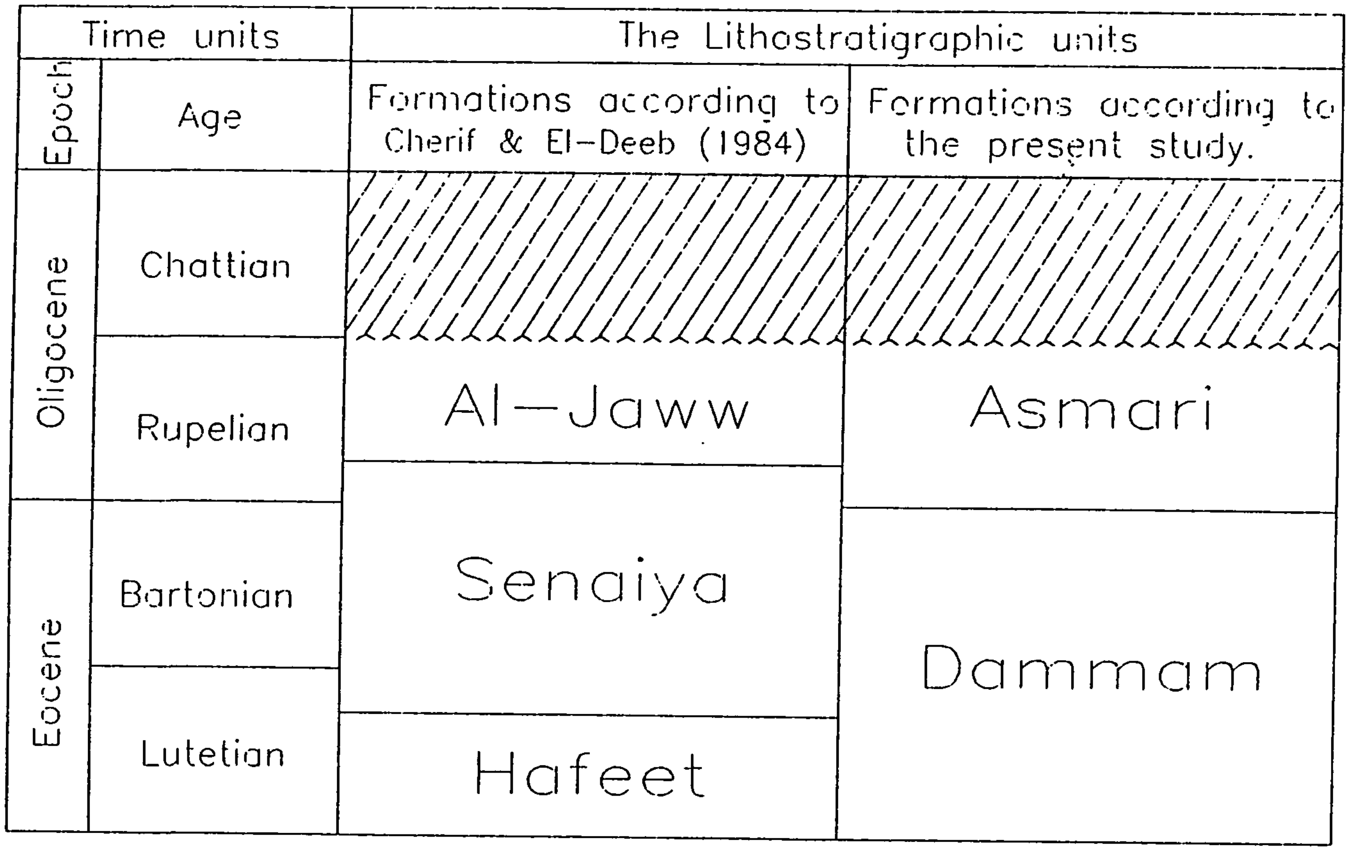


Fig.11 : Comparison between the previous lithostratigraphic study and the present study on the Jabal Hafeet section.

These names were preceded by both the Dammam and Asmari Limestones which are deeply entrenched in both the Arabian and the Arabian gulf Paleogene stratigraphy, and hence are preferred here for these newly introduced and much localized names. Consequently, the names Hafeet, Senayciah and Al-Jaww are here dropped and are replaced by both the Dammam and Asmari Limestones (fig.11).

The Hafeet Formation has been proved to be the lateral equivalent of the Dammam Formation as it has exactly the same lithology and the fossil content (see owen & Nasr, 1958; Powers and others, 1966; Powers, 1968; Sander, 1962; El-Nakhal, 1973; Tleel, 1973; Al-Tamimi, 1985 and El-Nakhal & El-Naggar, 1989). However, in more complete sections such as in the subsurface of the U.A.E. (*cf.* Pinnington, 1981; ADMA report, 1985) and in the subsurface of Interior Oman (*cf.* Clarke, 1988) the Dammam Formation was found to extend to the Late Eocene age. Consequently, it is here suggested to include Middle - Late Eocene successions with the typical Dammam facies under the term Dammam *sensu lato* . This covers both the Hafeet and most of the Senayciah Formations, and makes such restricted terms only worthy of being dropped.

Again, both the upper part of the Senayciah and the overlying Al-Jaww Formations have been proved to be the lateral equivalents of the Asmari Limestone as they have the same lithology and fossil content of the Oligocene Asmari Formation in the subsurface of the U.A.E. as well as in both outcrop and subsurface sections of southwestern Iran (*cf.* Thomas, 1950; James and

Wynd, 1965; Pinnington, 1981 and ADMA report, 1985).

Moreover, less than 30 km south of the Jabal Hafeet area, a number of exploratory wells (e.g Suneinah-1, and Shams-1) have penetrated both the Paleogene and the Cretaceous successions. In these wells The identified Dammam, Umm Al Rua'us (Rus) and Umm Al Radhuma Formations are overlying the Simsimah Formation and underlying the Asmari Limestone. Also, in both onshore and offshore sections of the U.A.E the Dammam Formation is described to occupy a similar stratigraphic position, overlying the Pabdeh Formation and underlying the Asmari Formation.

From the above mentioned discussion, it becoames obvious that the Late Eocene - Early Oligocene section of the northern part of Jabal Hafeet should preferably be included under the Dammam and Asmari Formations as follows:

II.5.1 The Dammam Formation in the Studied Section:

This Late Eocene part of the Dammam *s.l.* Formation (fig.12) is represented by a thickness of about 100 m (samples 1-16). It equates the obsolete Members B, C, and D of the Senayciah Formation of Cherif and El-Deeb (1984) and is composed of detrital, skeletal, glauconitic, marly limestone (that is partially recrystallized, bioturbated, locally stylolitized, and sporadically iron stained). The fossil assemblage is very diverse, including both benthonic and planktonic foraminifera, bryozoa, echinodermata, and red calcareous algae, of these, the following forms have been identified: *Nummulites fabianii* (Prever), 1905, *N. retiatus* Raveoda, 1959, *N. striatus* (Bruguiere), 1792,

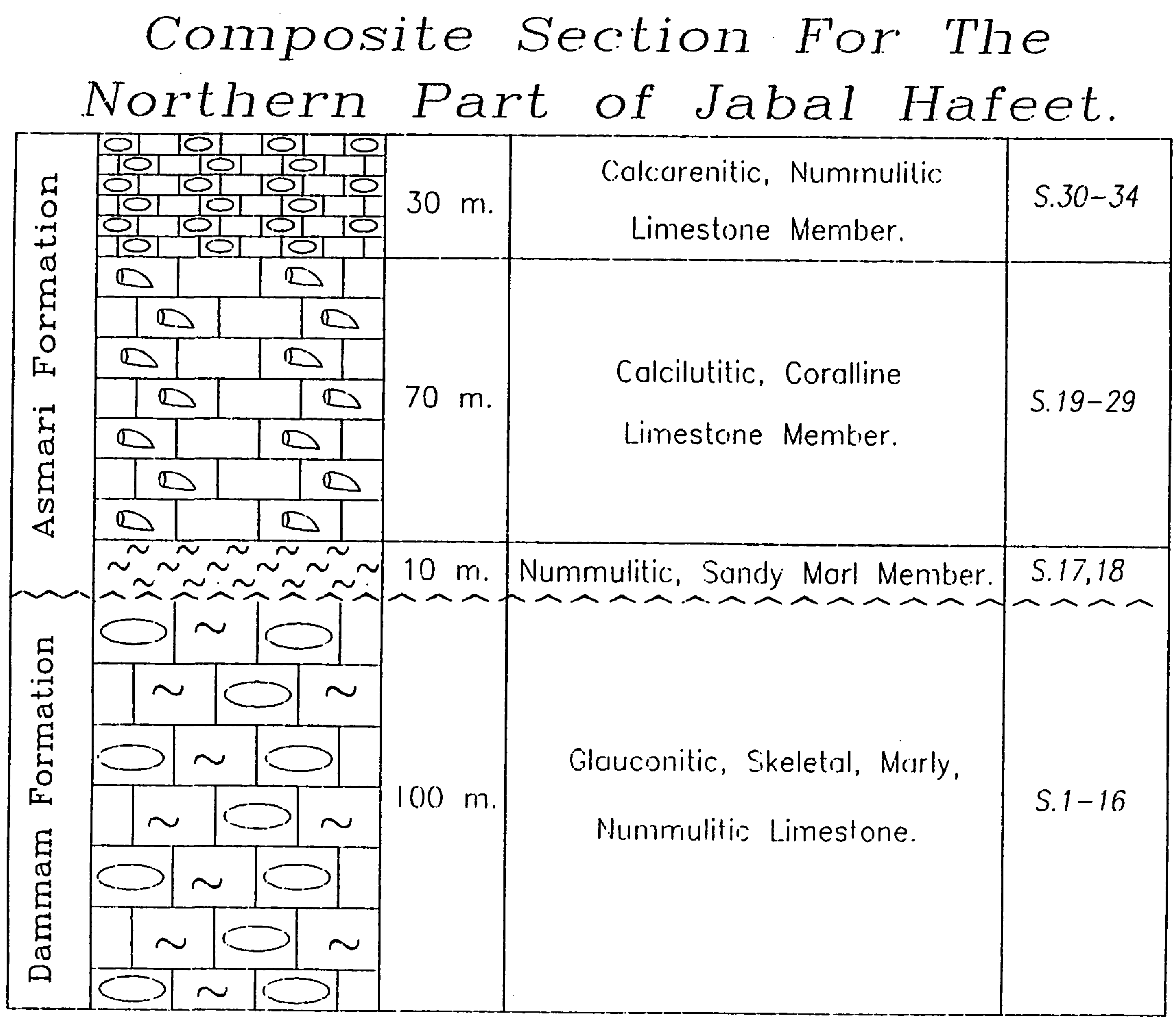


Fig.12 : Composite section for the northern part of Jabal Hafeet.

N. orbignyi (Galcotti), 1837, *N. incrassatus* De La Harpe, 1883, *N. bouillei* De La Harpe, 1879, *Heterostigina sp.*, *Spiroclypeus sp.*, *Discocyclina sp.*, *Chapmanina sp.*, *Rotalia sp.*; *Quinqueloculina sp.* *Triloculina sp*, *Biloculina sp*, *Peneroplis sp*, *Spirolina sp.*, *Fusarchaias sp.*, *Orbitolites sp.*, *Praerhapidionina sp.*; *Guttulina sp.*; *Bulmina sp.*, *Uvigerina sp.*; *Turborotalia centralis* and *Globigerinatheka sp.*

The presence of *N. fabianii* suggests a correlation with the *N. fabianii* (*sensu lato*) Zone of Pomerol (1982) of Late Eocene age. However, the presence of *N. retiatus* restricts this age to the late Late Eocene as it correlates this part of the succession with *N. retiatus* Zone of Pomerol (*op. cit*) which is restricted to that age. This age assignment is further supported by the presence of both *N. bouillei* and *N. retiatus* in the uppermost part of the Dammam *s.l.* Formation of the studied section.

II.5.2 The Asmari Formation In The Studied Section:

The Asmari Formation (fig.12) is represented by a thickness of about 110 m (samples 17-34). It is equated with both the obsolete E Member of the Senayciah Formation and the overlying Al-Jaww Formation, of Cherif & El-Deeb (1984).

The Asmari Formation in the Jabal hafeet area can be, lithologically, subdivided into three members, from bottom to top as follows:

-The Lower Sandy Marl Member:-

This member is represented by a thickness of about 10 m (samples 17,18). It is composed of sandy marls, that are highly dolomitized and extensively iron stained, with late diagenitic gypsum veins, microsparite patches and glauconitic grains. Fossils identified in this member include *Nummulites bouillei, N. intermedius, N. vascus, Heterostigina sp., Textularia sp. and Nodosaria sp.* The presence of *Nummulites intermedius* suggests a correlation with the *N. intermedius* Zone of Pomerol (1982) of Early Oligocene age.

-The Middle Reefal Limestone Member:-

This member is represented by It attains a thickness of about 70 m in the studied section (samples 19-29). It is composed of creamy, calcilutitic, coralline limestone, which is partially dolomitized, and occasionally recrystallized. Fossils identified in this member is limited to a few *Nummulites bouillei, N. intermedius, N. vascus; Heterostigina sp.; Discocyclina sp.; Borelis sp.* abundant miliolid remains, red calcareous algae, colonial and solitary corals, ostracods and rare planktonic foraminiferid remains. According to both its fossil content and stratigraphic position, this member is here assigned an Early Oligocene age.

-The Upper Nummulitic Limestone Member:-

This member is represented by a thickness of about 20 m in the studied section (samples 30-34). and is composed of light brown, calcarenitic, fossiliferous limestone, partially recrystallized, locally dolomitized, and rarely iron stained. The fossil content of this member is similar to the underlying one except for the abundant remains of colonial, reef-builders (e.g. corals, algae, bryozoa, etc.). The benthonic foraminifera include *Nummulites vascus*, *N. intermedius*, *Heterostigina sp.*; *Operculina complanata*; *Discocyclina sp*, *Borelis sp.*, *Victoriella sp.*, *Lithothamnium sp*, *Archaeolithothamnium sp.*, *Lithophyllum sp.*, *Corallina prisca*; together with abundant Miliolid; bryozoan, algal and Echinodermal remains (spines, plates and debris). The identified fossil assemblage in this member suggests a Middle Oligocene age.

III.MICROFACIES ANALYSIS

III.1 General Discussion

The term "facies" was, originally, introduced in the geologic literature as early as 1669 by Nicolas Steno but its modern scientific usage is credited to the Swiss geologist Amanz Gressly, who used the term in 1838 in describing the Upper Jurassic succession of the Jura Mountains (Reading, 1978). The term has since been the subject of considerable debate (*cf.* Krumbein and Sloss, 1963). Stratigraphically, the term is used to mean a body of rocks as distinguished from other bodies of different appearance, composition or fossil content, or only a lateral subdivision of a stratigraphic unit on the basis of such, and hence the compound terms lithofacies, biofacies, tectofacies, etc. The term was introduced by Brown (1943) to mean any criterion defining a rock in thin section, then it was reintroduced by Cuvillier (1951) to mean both the paleontologic and petrographic criteria defining a rock in thin section.

Flugel (1982) defined the term microfacies as "the total of all the paleontological and sedimentilogical criteria which can be classified in the thin sections, peels and/or polished slabs" and considered this definition to be just a methodological refinement of Gressly's classical facies concept and definition.

Following Cuvillier's concept of depositional interpretations of microfacies, Wilson (1975) compiled and interpreted the different microfacies types already introduced, and redefined them using either Dunham's (1962) or Folk's (1962) textural classification combined with Flugel's (1972) paleontological observations. The product was a number of standard microfacies types, grouped into a limited number of facies belts which when laterally disposed can construct a generalized model. Despite its oversimplification, this model surprisingly shows its regular facies sequence in different tectonic settings and is so persistent that, it can predict the geographical distribution of many different rock types (Wilson, *op.cit.*).

Modern facies associations can be found in ancient environments and hence can act as visual models for the interpreted, ancient ones. When they are portraying and interpreting both the lateral and vertical facies distribution and predicting where the undiscovered facies may be found, at a particular time and under a fixed pattern of processes, facies models are said to be static. However, when such models are used in interpreting both the lateral and vertical facies distribution under variable conditions; or in other words when they are used in interpreting various patterns of environments in both the vertical and the lateral dimensions, they are said to be dynamic. Therefore, facies models can be used as strong tools for field mapping, rock units correlation and, for facies - controlled economic ore deposits (such as oil and gas, coal, phosphate and other economic sedimentary ore deposits).

Despite the very thick, oil producing carbonate sequences of both Arabia and the Arabian gulf basin, microfacies studies in the region are limited to the works of Bozorgnia and Banafti (1964) and Sampo (1969) in Iran and the specific works on the Paleogene of Saudi Arabia by Kamel (1985), Wasimuddin

Microfacies Analisys Of The Studied Section In Jabal Hafeet

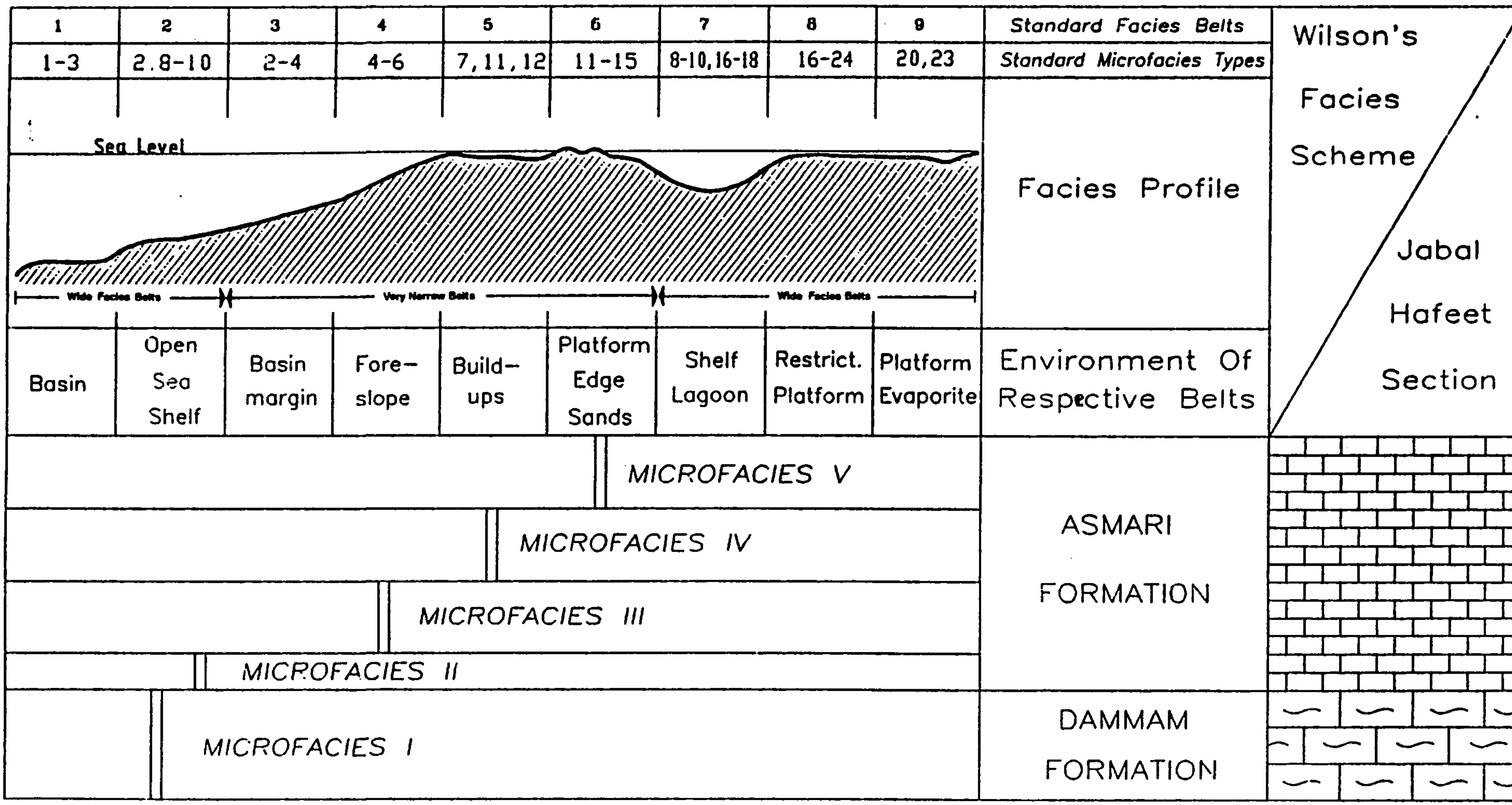


Fig.13 : Microfacies analysis of the studied section in Jabal Hafeet.

(1985) and Al-Tamimi (1985); the Paleogene of Kuwait by El-Nakhal and El-Naggar (1989) and the Paleogene of Iraq by Buday (1985).

III.2 Microfacies Analysis Of The Studied Section:

No microfacies analysis for the studied section has ever been attempted before. Consequently, selected samples of the Late Paleogene succession of Jabal Hafeet have been thin sectioned for their microfacies analysis (fig.13). This was carried out using both the textural classification of Dunham (1962) as expanded by Embry and Klovan (1971) and the latest foraminiferal classification by Loeblich & Tappan (1988). Each of these recognized microfacies was compared with both Wilson's (1975) standard microfacies types and standard facies belts, wherever possible and its paleoenvironmental condition of deposition was interpreted. The age of each microfacies was also interpreted on the basis of the abundant Nummulitid and sparse planktonic Foraminiferid remains (*cf.* Blondeau, 1972; Bolli and Others, 1988). The recorded microfacies are described (from base to top) as follows:-

III.2.1 The Glauconitic, Peloidal, Nummulitic Marly Packstone / Wackestone Microfacies (*with N. fabianii / N. retiatus*) (Microfacies I; Pls. 1-14):-

This microfacies is represented by intraclastic, peloidal, skeletal, argillaceous packstone - wackestone. The matrix is mainly microcrystalline calcite, partially recrystallized into micro- and pseudosparites. The intraclasts are mainly plasticlasts, while the peloids are of the Bahamitic variety. The skeletal grains are either biomorpha (whole fossils) or bioclastic (skeletal fragments).

This microfacies is disseminated with glauconite grains, occasional silt- sized quartz grains some iron staining, bioturbation and irregular to columnar microstylolites, with associated microstylocumulates (insoluble material such as clay minerals, pyrite, dolomite, and organic substances concentrated along the suturing).

This microfacies represents the uppermost part of the Dammam Formation which is usually missing in most of the Arabian Peninsula due to the late Paleogene uplift and non - deposition, or deposition followed by subsequent erosion. The presence of *Nummulites fabianii*, *N. retiatus*, *N. striatus*, *N. chavannesi*, *N. incrassatus*, and *N. orbignyi* correlates this horizon with the Late Eocene *N.fabianii* (*sensu lato*), Zone of Pomerol (1982). However, the presence of *N.retiatus* restrict the age of this part of the succession to the latest Eocene as *N.retiatus* is only recorded in the latest phase of the Late Eocene (*cf.* Pomerol, 1982).

The glauconitic, peloidal, Nummulitic marly packstone/wackestone microfacies is also correlated with the bioclastic wackestone Standard Microfacies (SMF#9) of Wilson (1975). This SMF can be found in either the Standard Facies Belts#2 (open sea shelf) or the Standard Facies Belt # 7 (open platform or shelf lagoon). However, the former paleoenvironmental interpretation (open sea shelf) is more appropriate here due to the abundance of stenohaline organisms such as bryozoa, echinodermata and red calcareous algae.

Such stenohaline forms usually live in depths much greater than that of the shelf lagoon *cf.* Flugel,1982). Again, the presence of both marls and glauconite grains which are usually formed at depths that range between 50 and 500 m in the marine domain (*cf.* Lewis,1984)is a further support for the open sea shelf paleoenvironment interpretation for this microfacies. This is substantiated by both comparing the recorded forms with the chart of depth ranges prepared for living groups of organisms by Flugel (1982) and by the fact that this facies is represented by argillaceous packstone / wackestone.

Indeed, Tucker (1990), mentioned that argillaceous packstone-wackestone facies are usually found in offshore areas, forming the base of shallowing upward carbonate cycles. This statement seems to be well-fitting here, as the studied Late Paleogene carbonate succession has been proved to represent a steadily shallowing upward cycle (fig.13).

III.2.2 The Glauconitic, Dolomitic, Skeletal, Sandy, Wackestone Microfacies (Microfacies II; Pl.15):-

This microfacies is composed of glauconitic, fossiliferous sandy marly wackestone, which is highly dolomitized, extensively iron stained and locally traversed by gypsum veins. The matrix is composed of brownish calcareous shaly material, that is highly dolomitized and iron stained. The skeletal grains are mainly in the form of biomorpha and bioclasts that are generally unaltered. The sand grains are fine and subangular, suggesting a relatively nearby source area. The dolomite crystals are fine to medium sized, showing iron oxide inclusions and wavy extinction, which are characteristic for the ferroan dolomite. Such dolomitization is believed here to belong to the burial dolomitization model. The principal mechanism of this model is the dewatering of the nearby basinal, organic rich shales with the expulsion of fluids enriched in Mg^{2+},Fe^{2+},Ca^{2+}, Si^{4+} and Na^{+} into an adjacent shelf edge and platform carbonates (*cf.* Tucker, 1990). The Mg^{2+} rich fluids are derived from the transformation of the montmorillonite and smectite to illite as a result of compaction, with increased burial and rising temperature (cf. Boles and Francks, 1979; Mattes and Mountjoy, 1980; Mchargue and Price, 1982; Scoffin, 1987).

The neritic, open sea, shelf edge platform carbonates of the Dammam Formation in the studied area grades laterally towards the deeper part of the basin in the subsurface of offshore Dubai into the the more basinal Pabdeh Formation, which replaces the whole Paleogene succession including the Dammam Formation. This basinal shaly formation can act as a source for the Mg^{2+} rich fluids.

Another source for such fluids would be the high Mg calcite of the skeletal fragments included in the Dammam *s.l.* Formation. These could have been transformed into the more stable, low Mg-calcite releasing the Mg-rich fluids (*cf.* Goodell & Garman, 1969; Mckenzie, 1981). The richness of this microfacies in both Mg^{2+} and Fe^{2+} is evidenced by the abundant dolomitization, the presence of glauconite grains and the dark brown color of the rock indicating later oxidation of the iron minerals by weathering.

This microfacies represents the basal part of the Asmari formation. The presence of *Nummulites intermedius*, *N.vascus* and *N.bouillei* suggests a correlation with the Oligocene

N.intermedius zone of Pomerol (1982), and the presence of *N.bouillei* restricts the age to the Early Oligocene.

The glauconitic, dolomitic, skeletal, sandy marl microfacies could not been correlated with any of the Standard Microfacies of Wilson (1975). However, it is here taken to represent an open platform shelf conditions, on the basis of the abundance of the marls which usually characterize such an environment (Flugel,1982).

III.2.3 The Algal Floatstone Microfacies (Microfacies III; Pls.16-18):

This microfacies is represented by oncoidal floatstone, with a microcrystalline calcite matrix and some sparite veins. The skeletal grains are either algal biomorpha or algal oncoids in the form of a solid nuclei surrounded by biogenic coatings of red calcareous algae. Dolomitic veins and Geopetal fillings are common.

This is the second microfacies from the base of the Asmari Formation upwards. The formation is typically represented by reefal limestones on the Iranian side of the basin (*cf.* Sampo 1969), and is also developed as reefal limestones in Jabal Hafeet. The presence of both the *Victoriella sp.* and the *Subterranipyllum thomasi* substantiates the Oligocene age of this part of the section which conformably overlies typical Early Oligocene rocks with *Nummulites intermedius*, *N. vascus* and *N. bouillei.*

This microfacies is here correlated with the floatstone Standard Microfacies (SMF # 5) of Wilson (1975), which is usually found in the foreslopes of the continental shelf (facies belt # 4). The paleoenvironmental interpretation of this microfacies as a common fore-reef flank is supported by the abundance of the skeletal debris (marine talus) that have been carried down from the upslope of the reef buildups to their fore-reef flank environment. The slope of the Fore-reef flank varies greatly, and can be reach up to 30° , allowing the debris to be deposited on the inclined surface, which could later on develop into a ramp (Wilson, 1975).

III.2.4 The Reefal Boundstone Microfacies (Microfacies IV; Pl.19):

This microfacies is represented by fossiliferous biolithite or bioclastic bafflestone. The matrix is generally microcrystalline calcite, while the skeletal grains are represented by corals and some encrusted and trapped benthonic foraminifera. Such skeletal grains seem to have been bound together during deposition, and the rock shows borings that are partially filled with sparry calcite. Subsequent leaching is also evidenced by the presence of some intraparticle porosity.

This is the third microfacies from the base of the Asmari Formation upwards. It is here correlated with the organic reef buildups {Boundstone Standard Microfacies (SMF # 7) of Wilson ,1975}. It reflects a paleoenvironment of an

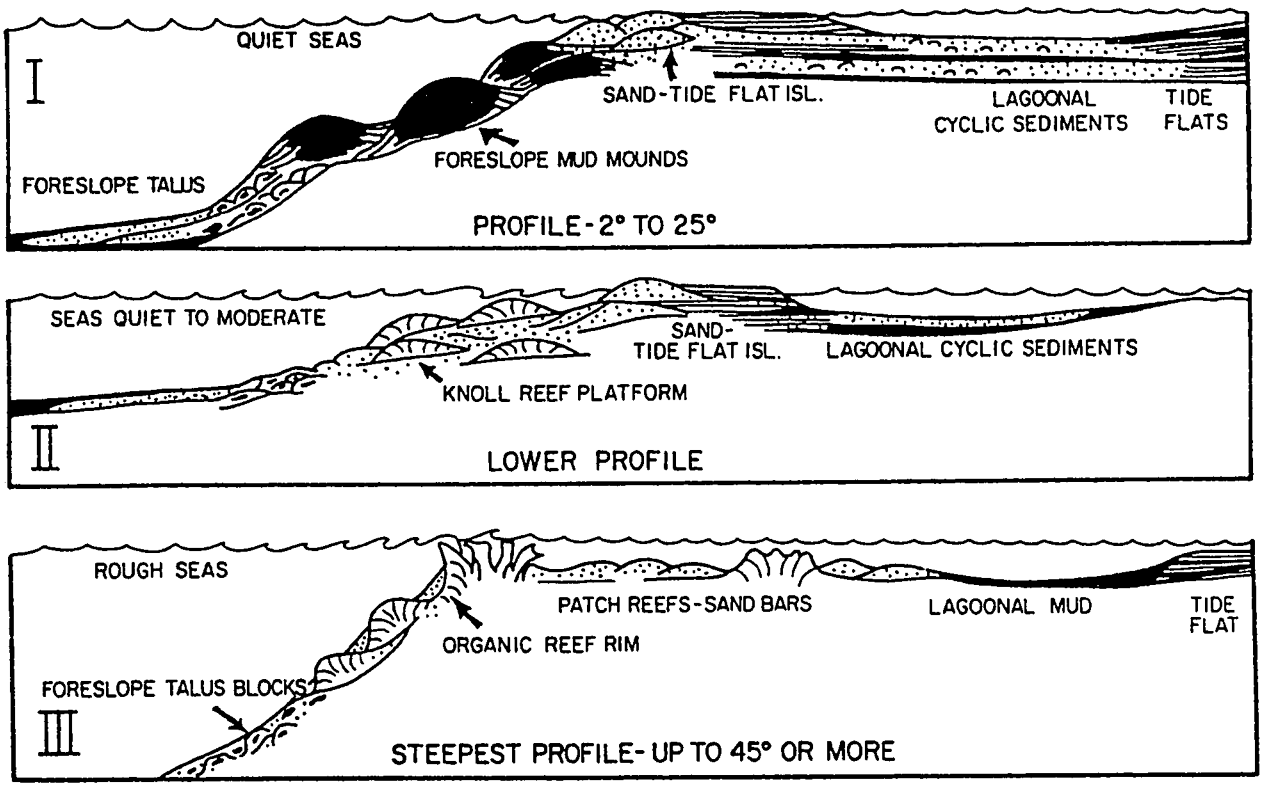


Fig. (14) Three types of carbonate shelf margins: I, downslope lime-mud accumulation; II, knoll reef ramp or platform; III, organic reef rim. From Wilson (1974, Fig. 1).

organic reef buildup at the platform margin, composed of patches of organic boundstone (bafflestone) with interstitial lime mud downslope (as shown in the previous microfacies) and packstone upslope (as will be shown in the next microfacies). This microfacies represents either the knoll reef ramp or platform shelf margin (type II), or the organic reef rim margin (type III), both are of Wilson's (1974) Shelf margin types (fig.14). However, type III is here favoured on the basis of both the absence of skeletal debris (which characterize type II) and the presence of limesand behind the reef - as will be shown in the next microfacies- (which characterizes type III). The Reefal Boundstone Microfacies is considered here to be of Early Oligocene age on the basis of its stratigraphical position, conformably underlain and overlain by well-dated Early Oligocene rock units.

Indeed, similar reefal facies have already been recorded in the Oligocene successions of both southwestern Iran (*cf.* Thomas, 1950; Bozorgnia and Banafti, 1964; James and Wynd, 1965; Sampo, 1969) and Northern Iraq (the Kirkuk Limestone) by Henson (1950), van Bellen (1956) and Dunington (1958).

III.2.5 The Dolomitized, Peloidal, Nummulitic Packstone (with *N. intermedius/N. vascus*); (Microfacies V; Pls.20-22):

This microfacies is represented by peloidal bioclastic packstone. The matrix, whenever found, is made of microcrystalline calcite crystals and is frequently dolomitized. The skeletal gains are either composed of bioclasts or biomorpha. The bioclasts are mainly in the form of foraminiferal and algal debris, while the biomorpha are predominantly composed of abundant, well preserved tests of *Nummulites intermedius*, *N.vascus*, *N.spp.* and *Heterostigina spp.* In addition to bryozoan, echinodermata, and algal remains (red calcareous algae) are present.

This microfacies constitutes the uppermost unit of the Asmari Formation in the studied section. It is followed disconformably with the Miocene Lower Fars Formation, which is not included here. The presence of both *Nummulites intermedius* and *N.vascus* correlate this part of the Jabal Hafeet section with the *N.intermedius* Zone of Pomerol (1982) which is of Early to Middle Oligocene age. The Dolomitic Peloidal Nummulitic Packstone Microfacies is also correlated with the coquina, bioclastic grainstone Standard Microfacies (SMF#12) of Wilson (1975), which is usually found on the winnowed platform edge. Such coquinoidal grainstone is normally deposited in back-reef environments where constant wave or current action, usually removes mud fractions by winnowing, and hence it is taken to characterize the edge of the platform environment. However, this microfacies is very rich in skeletal debris together with a considerable amount of lime mud. This implies that either the current action was not strong enough to remove all the mud downslope, allowing the sediments to evolve into grainstone, or the slope was not steep enough for the lime mud to move downslope. Hence this microfacies can be considered as a variety of SMF#12 of Wilson (1975).

From the above listed microfacies analysis, it can be concluded that the Late Eocene - Early Oligocene succession of Jabal Hafeet was deposited as a steadily shallowing upward sequence (fig.13). This started with open marine shelf conditions in the Late Eocene time (Microfacies I) moving to basin margin conditions in the earliest Oligocene time (Microfacies II) then to Foreslope conditions in the Early Oligocene time (Microfacies III) to reef buildup towards the middle of the Early Oligocene (Microfacies IV), to back-reef winnowed platform edge towards the late Early Oligocene time (Microfacies V). These were either followed by lagoonal restricted platform and platform evaporites that were later on eroded during the post-Asmari uplift and erosion, or were not deposited at all in the Jabal Hafeet area. The fact that the Early Miocene Lower Fars Evaporites which unconformably caps the Asmari Limestone in the Jabal Hafeet section may support the former interpretation and hence represent the shelf lagoonal phase of the shallowing upword carbonate cycle in this area. The succession is more complete in southwestern Iran where the Asmari Formation represents the whole of the Oligocene and parts of the Early Miocene. The section gradually approaches completion when followed northward of Jabal Hafeet towards offshore Iran.

IV. SYSTEMATICS OF THE RECORDED FORAMINIFERIDA

A total of 33 foraminiferal and algal species have been identified, and correlated with previous records in and outside the region (*cf.* Ellis and Messina, 1966; Majewske, 1969; Sampo, 1969); Horowitz and Potter, 1971; Blondeau, 1972; Scholle, 1978; Haynes, 1981; Beckmann and others ,1982; Flugel, 1982; Cherif and El Deeb, 1983a,b; Adams and others, 1984 and Sartorio & Venturini,1988). The foraminiferal species belong to 24 genera, 8 subfamilies, 13 families, 8 superfamilies and 5 suborders of the Order Foraminiferida. These are systematically listed according to the latest classification of Loeblich and Tappan (1988), as follows:-

Order: **FORAMINIFERIDA** Eichwald, 1830

1-Suborder: **TEXTULARIINA** Delage & Herouard, 1896

Superfamily: **ORBITOLINACEA** Martin, 1890

Family: **ORBITOLINIDAE** Martin, 1890

Subfamily: **DICTYOCONINAE** Moullade, 1965

Genus: ***Dictyoconus*** Blanckenhorn, 1900

Species: ***Dictyoconus sp.***

2-Suborder: **MILIOLINA** Delage & Herouard, 1896

Superfamily: **MILIOLACEA** Ehrenberg, 1839

Family: **HAUERINIDAE** Schwager, 1876

Genus: ***Pyrgo*** Defrance, 1824

Species: ***Pyrgo spp.***

Genus: ***Quinqueloculina*** d'Orbigny, 1826

Species: ***Quinqueloculina spp.***

Genus: ***Triloculina*** d'Orbigny, 1826

Species: ***Triloculina spp.***

Superfamily: **SORITACEA** Ehrenberg, 1839

Family: **SORITIDAE** Ehrenberg, 1839

Subfamily: **SORITINAE** Ehrenberg, 1839

Genus: ***Orbitolites*** Lamarck, 1801

Species: ***Orbitolites complanatus*** Lamark, 1801

Subfamily: **FUSARCHAIASINAE** Saidova, 1981

Genus: ***Fusarchaias*** Reichel, 1952

Species: ***Fusarchaias operculiniformis*** Henson, 1944

Species: ***Fusarchaias spp.***

Subfamily: **PRAERHAPYDIONININAE** Hamaoui & Fourcade, 1973

Genus: ***Praerhapydionina*** Van wessem, 1943

Species: ***Praerhapydionina delicata*** Henson, 1950

Family: **PENEROPLIDAE** Schultze, 1854

Genus: ***Peneroplis*** de Montfort, 1808

Species: ***Peneroplis spp.***

Genus: ***Dendritina*** d'Orbigny, 1826

Species: ***Dendritina spp.***

Genus: ***Spirolina*** Lamarck, 1806

Species: ***Spirolina austriaca*** d'Orbigny

Species: ***Spirolina spp.***

Family: **ALVEOLINIDAE** Ehrenberg, 1839

Genus: ***Borelis*** de Montfort, 1808

Species: ***Borelis sp.***

3-Suborder: **GLOBIGERININA** Delage & Herouard, 1896

Superfamily: **GLOBIGERINACEA** Carpenter, Parker & Jones, 1862

Family: **GLOBIGERINIDAE** Carpenter, Parker & Jones, 1862

Subfamily: **PORTICULASPHAERINAE** Banner, 1982

Genus: ***Globigerinatheka*** Bronnimann, 1952

Species: ***Globigerinatheka sp.***

Superfamily: **GLOBOROTALIACEA** Cushman, 1927

Family: **GLOBOROTALIIDAE** Cuchman, 1927

Genus: ***Turborotalia*** Cuchman & Bermudez, 1949

Species: ***Turborotalia centralis*** (Cuchman & Bermudez, 1937)

4-Suborder: **LAGENINA** Delage & Herouard, 1896

Superfamily: **NODOSARIACEA** Ehrenberg, 1838

Family: **POLYMORPHINIDAE** d'Orbigny, 1839

Subfamily: **POLYMORPHININAE** d'Orbigny, 1839

Genus: ***Guttulina*** d'Orbigny, 1839

Species: ***Guttulina sp.***

5-Suborder: **ROTALLINA** Delage & Herouard, 1896

Superfamily: **ROTALIACEA** Ehrenberg, 1839

Family: **ROTALIIDAE** Ehrenberg, 1839

Subfamily: **ROTALIINAE** Ehrenberg, 1839

Genus: ***Rotalia*** Lamarck, 1804

Species: ***Rotalia spp.***

Family: **CHAPMANINIDAE** Thalmann, 1938

Genus: ***Chapmanina*** A. Silvestri, 1931

Species: ***Chapmanina sp.***

Family: **DISCOCYCLINIDAE** Galloway, 1928

Genus: ***Discocyclina*** Gumbel, 1870

Species: ***Discocyclina spp.***

Genus: ***Orbitoclypeus*** A. Silvesteri, 1907

Family: **NUMMULITIDAE** de Blainville, 1829

Genus: ***Heterostegina*** de'Orbigny, 1826

Species: ***Heterostegina sp. cf. H. papyracea***

Heterostegina spp.

Genus: ***Nummulites*** Lamarck, 1801

Species: ***Nummulites bouillei*** De La Harpe, 1879

Nummulites budensis Hantken, 1875

Nummulites chavannesi De La Harpe, 1878

Nummulites fabianii (Prever), 1905

Nummulites incrassatus De La Harpe, 1883

Nummulites intermadius D'Archiac, 1846

Nummulites orbignyi (Galcotti), 1837

Nummulites retiatus Raveoda, 1959

Nummulites striatus (Bruguiere), 1792

Nummulites vascus Joly & Leymeric, 1848

Genus: ***Operculina*** de'Orbigny, 1826

Species: ***Operculina complanata*** Defrance, 1822

Operculina spp.

Genus: ***Spiroclypeus*** H. Douville, 1905

Species: ***Spiroclypeus sp.***

Superfamily: **PLANORBULINACEA** Schwager, 1877

Family: **VICTORIELLIDAE** Chapman & Crespin, 1930

Subfamily: **VICTORIELLINAE** Chapman & Crespin, 1930

Genus: ***Victoriella*** Chapman & Crespin, 1930

Species: ***Victoriella sp.***

Added to these, a rich assemblage of red calcareous algal remains has also been identified. The identified algal species include: *Lithothamnium sp.*; *Archaeolithothamnium sp.*, *Lithophyllum sp.* and *Subterraniphyllum thomasi.* Similarly, abundant bryozoan, molluscan and echinodermal skeletal remains have been recorded, but these were found to be too fragmentary to warrant either identification or classification.

V.THE GEOLOGICAL EVOLUTION OF JABAL HAFEET

Jabal Hafeet is described as a whale back, almost north-south trending, northerly plunging anticline (figs.3,15), (Searle and others, 1983). The geologic evolution of such a structure involved the deposition of its relatively thick carbonate sequence (about 400 m) in the Omani foreland basin, followed by the emergence of this sedimentary pile (fig.16). such emergence was apparently the product of of post depositional crustal shortening and telescoping, that had accompanied the Zagros Orogeny.

V.1 Successive Stages In The Development Of Jabal Hafeet:-

V.1.1 The Evolution of the Omani Foreland Basin:-

The eastern margin of the Arabian plate was a site of carbonate deposition since -at least-the Early Permian time (*cf.* Murris, 1980). This carbonate deposition was virtually uninterrupted until the Late Triassic, when rifting resulted in the establishment of a passive continental margin with a shelf edge and a small ocean basin known as the Neo-Tethys (*cf.* Searle and others, 1983). In this ocean basin the Jurassic - Early Cretaceous sequence was laid down in the form of a dominantly carbonate cycle over most of the Arabian plate. However, during the Middle-Late Cretaceous time the passive continental margin of this plate was transformed into an active one that experienced collision, followed by underthrusting. The subduction resulted in the formation of a foreland basin in which Late Cretaceous - Paleogene sediments were laid

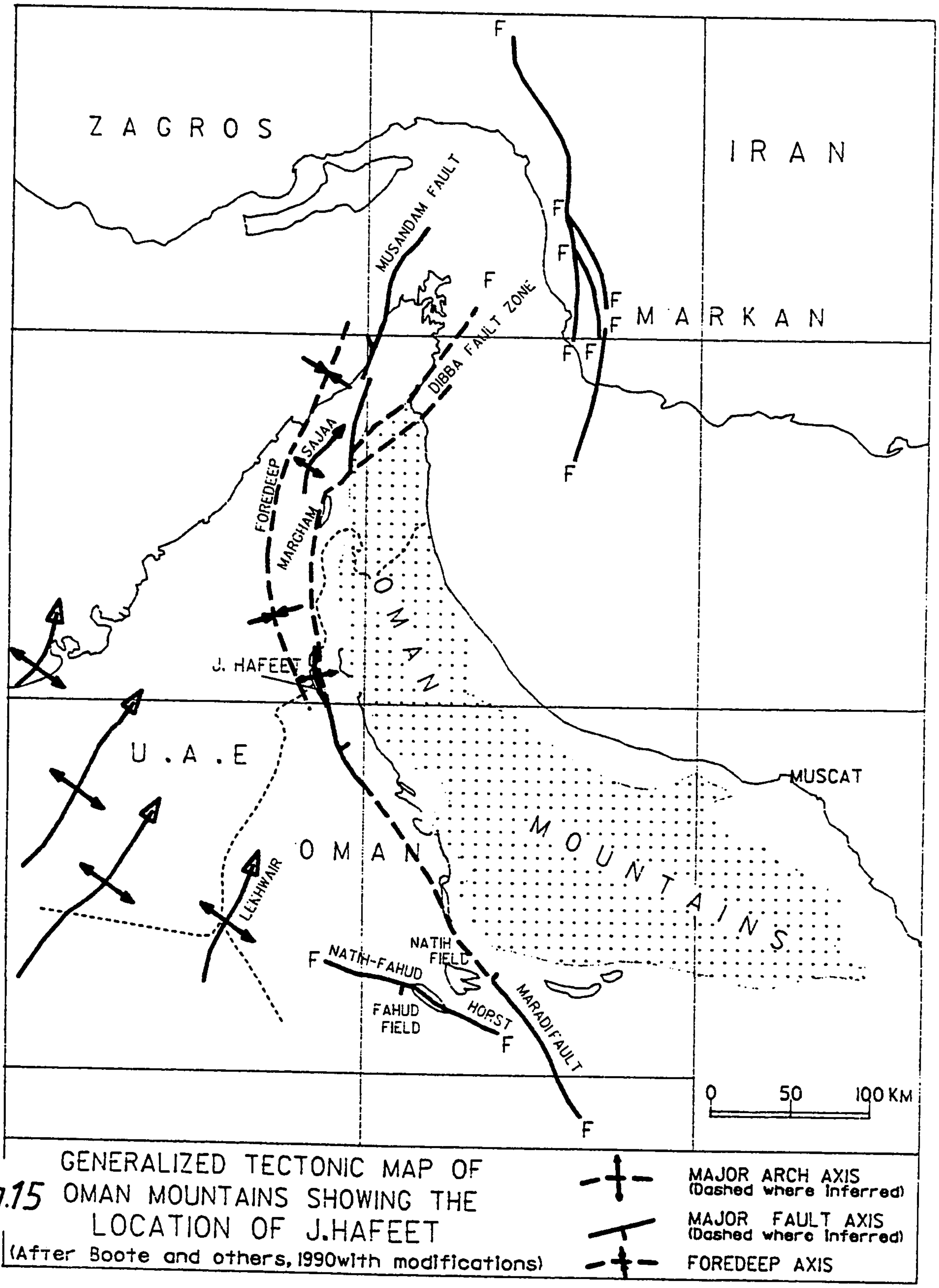


Fig.15 GENERALIZED TECTONIC MAP OF OMAN MOUNTAINS SHOWING THE LOCATION OF J.HAFEET
(After Boote and others, 1990with modifications)

down according to the following model:-

When thrusting began, the overthrusted load depressed the oceanic crust and resulted in the formation of a a flexural forebulge (or a peripheral swell) that uplifted the carbonate shelf edge of the extreme eastern part of the Arabian plate (*cf.* Stockmal and others ,1986). When the overthrusted load advanced, the continental margin was further depressed and the swell migrated cratonward, resulting in a drastic downwarping of its former position and the development of the Omani foreland basin (*cf.* Robertson ,1987; and Patton and O'Connor,1988). In this basin the Late Cretaceous - Paleogene sequence was laid down as follows:

(1) At the onset of the Cenomanian Time:

As a result of major uplifting in eastern Arabia, the deposition of shelf carbonates over this part of the Arabian plate ended suddenly during the Cenomanian time (*cf.* Murris, 1980; Searle and others, 1983). This marked the initial growth of a peripheral swell at the plate margin, extending from south of the Fahud Field, northward to eastern Abu Dhabi (*cf.* Harris and Forest, 1984; Patton and O'Connor, 1988; etc.). The emergence of this swell was characterized by both block faulting and erosion (*cf.* Robertson, 1987), and the process was further enhanced by the global low sea stand during this age (*cf.* Murris, *op.cit.*). Also during the Cenomanian, the Semail Ophiolite was initially obducted in a marginal basin, some distance northeast of the Arabian continental margin (*cf.* Pearce and others, 1981). Towards the end of this age, tensional block faulting was extensive over the swell, and constituted a zone that separated the Omani foreland basin, to the east from the intracratonic basin of the passive continental margin to the east {including offshore Abu Dhabi and parts of onshore Dubai-Ras Al Khaimah, and of eastern Saudi Arabia (*cf.* Harris and Forest, 1984; Al-Sharhan, 1989)}. The uplift of the swell was further enhanced by movements along old, deeply seated basement faults, and resulted in severe erosional truncations along the crestal parts of the produced swells (such as the Lekhwair Arch). Signs of contemporaneous erosion over the bulge which continued northward to the U.A.E. as a paleogeographic high were also recorded (*cf.* Boote and others, 1990).

(2) *During the Late Cenomanian-Turonian Time:-*

The emerged peripheral swell was subjected to intensive erosion as it continued its flexuring due to the increasing subduction of the continental lithosphere. This erosion truncated most of the Cenomanian - Turonian succession over crestal parts of the produced swells and resulted in the Wasia-Aruma break. This regional break marks the change from stable carbonate platform conditions prevailed prior to the Cenomanian time in eastern Arabia (or clastic/carbonate or even clastic conditions in central Arabia) to deep water unstable ones during the Santonian - Campanian time (*cf.* Patton and O'Connor, 1988).

(3) *During the Coniacian to Santonian Time:-*

The Arabian plate was involved in further subduction and downflexing along its margin. This resulted in the development of a relatively deep basin of deposition along that margin, in which a Late Cretaceous sequence was laid down. Such sequence include the deep water (300 - 500 m depth) Coniacian - Santonian Lower Fiqa Shale (*cf.* Glennie, 1974; Forest and others, 1980).

The Lower Fiqa Shale grades westwards into the Laffan Shale and other argillaceous limestone shelf sequences (*cf.* Pinnington and others 1981; Boote and others, 1990). and eastward into the Muti Conglomerates and turbidites of similar age, but of a much reduced thickness (*cf.* Searle and others, 1983).

It is worth mentioning that during the period between the Late Turonian and the Early Campanian time most of the deeply seated basement megastructures were in a state of activity. These include the Qatar arch (*cf.* Pinnington and others, 1981); The NNE-SSW anticlinal flexures of both Saudi Arabia and Abu Dhabi (*cf.* Murris, 1980) and the Fahud - Natih horst in Central Oman (*cf.* Tschopp, 1967b; Harris and Forest, 1984).

(4) *During the Campanian - Maastrichtian Time:-*

With the beginning of the Campanian, the landward migration of the peripheral swell was rapid (*cf.* Patton and O'Connor, 1988; Boote and others, 1990) and most of the Arabian margin dipped further to the east.

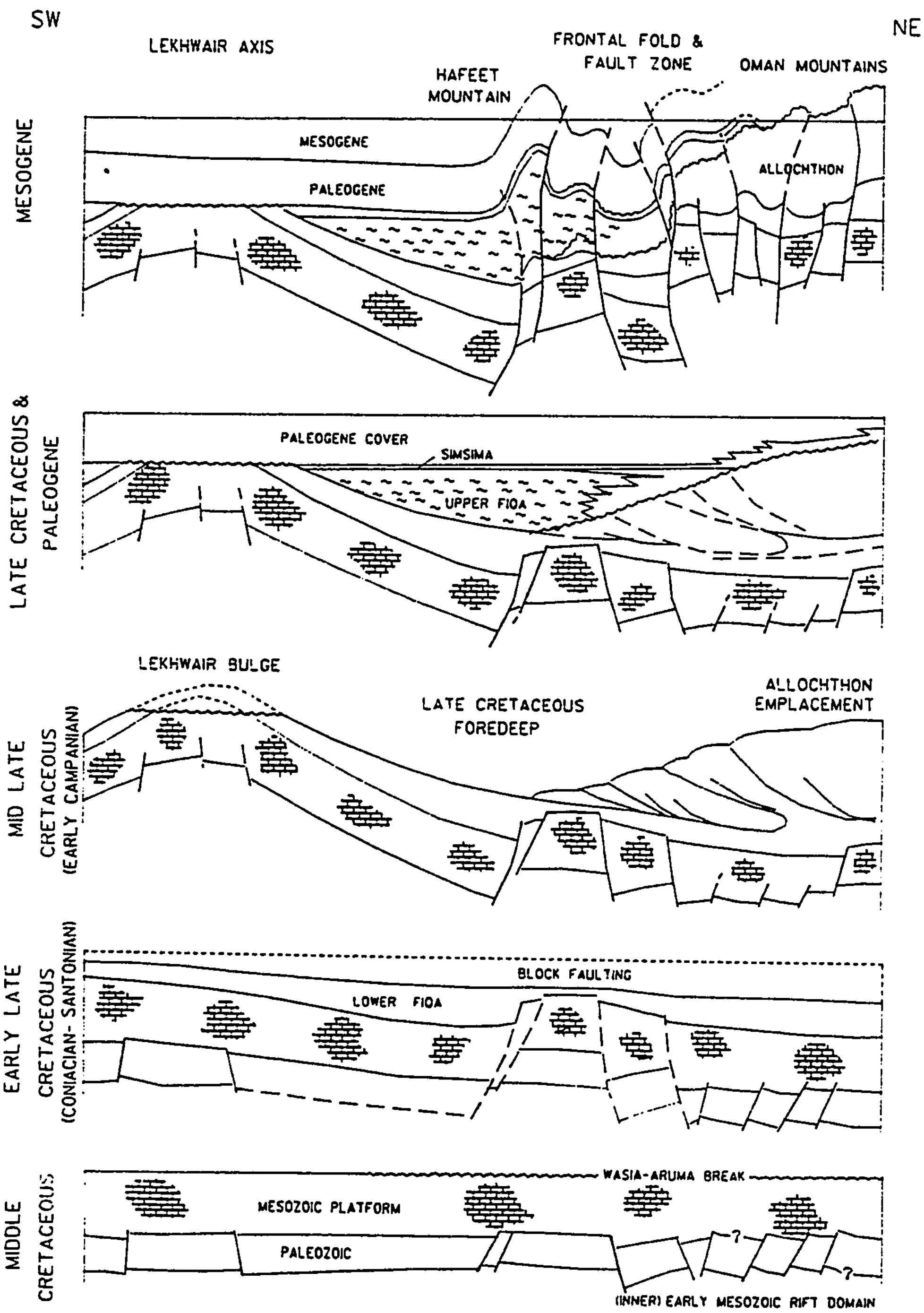


Fig.16 Mesozoic and Paleogene structural evolution of the Hafeet Mountain (after Boote and other, 1990)

Consequently, the overthrusted chunk of the oceanic crust (the Semail Ophiolite), gravitationally, slided over the underlying Lower Fiqa shale with multiple imbrication structures and tectonic pseudo thickening of the shale.

By the end of the Campanian, the thrusted sheets were available to erosion. This is evidenced by the presence of blocks of such sheets (the Semail Ophiolite) in the Late Campanian-Maastrichtian Juweiza Formation (*cf.* Searle and others, 1983). This overlies the Muti Formation in the east, while to the west, the upper Fiqa Formation continued to be deposited.

(5) *During The Late Maastrichtian Time:-*

The deformation associated with the multiple shortening and overthrusting of the eastern Omani continental margin spanned the time between the Turonian and the Early Maastrichtian (a period of about 20 m.y.). However, during the Late Maastrichtian, a major transgressive phase prevailed over the area and carbonate deposition was restored, resulting in the deposition of the Late Maastrichtian shallow marine Simsima Limestone (*cf.* Searle and others, 1983).

V.1.2 The Emergence of Jabal Hafeet:-

(1) *During The Paleogene Period:-*

Shallow marine carbonate and evaporite sedimentation was resumed over most of Eastern Arabia during the Paleocene - Middle Eocene, but marine Late

Eocene - Oligocene sediments are missing from most of the Arabian platform except for a small embayment that occupied the Omani Mountains foredeep (*cf.* Murris, 1980; Naqash and others, 1987; Beydoun, 1988). Early Paleogene sedimentation took place under apparently quite conditions, but the Late Paleogene witnessed one of the most active tectonic episodes in the geologic history of Arabia. This was probably directly connected with inception of the Zagros Orogeny, and hence the regression of the Late Eocene - Oligocene sea off the Arabian plate except for a small embayment that extended from western Iran to the central part of the Omani Desert. Even in such an embayment, smaller scale tectonic activities interrupted the pattern of sedimentation at least locally. This is apparent in the Jabal Hafeet area where several periods of small scale folding and faulting have resulted in a number of unconformities (*cf.* Cherif and El-Deeb, 1984).

The absence of Late Oligocene sediments in the Jabal Hafeet outcrop can either be attributed to non-deposition, following the global drop in the eustatic sea level during this age, or to erosion that followed such deposition. The assumption that the Jabal Hafeet area constituted part of the locally subsided Oman foredeep may substantiated the latter hypothesis and hence the belief that Late Eocene-Oligocene marine successions were deposited in that deep and were later eroded (*cf.* Naqash and others, 1987; Beydoun, 1988).

(2) *During The Mesogene Period:-*

The intensive Cenozoic tectonic activities in the region started towards the Latest Oligocene-Early Miocene time (*cf.* Beydoun, 1988; Searle and others, 1983; Naqash and others, 1987; Boote and others, 1990; Hanna, 1990). Such activities were directly connected with the Zagros Orogeny and were responsible for the deformation of most of the Mesozoic-Paleogene neoautochtonous cover. This deformation is mainly in the form of shallow folding known as the "whale back folds" (*cf.* Pinnington and others, 1981) which are similar in style to those of the Zagros fold belt. They form a narrow zone with a wave length that ranges between 5 and 15 km along the western coast of the Arabian gulf (*cf.* Murris, 1980; Searle and others, 1983).

A seismic section shot across the Jabal Hafeet areal (fig.17) shows that the Hafeet anticline is of a high amplitude, being bounded to the east by a steep, west-dipping fault zone with a high reverse angle, and to the west by a secondary bounding fault (Boote and others, 1990).

Different interpretations for the origin of the Jabal Hafeet structure have been put forward (*cf.* Cherif and El-Deeb, 1984; Naqash and others, 1987) but, the one accepted here is that it represents a drape fold. Such drape folding was initiated by a reverse slip, reactivation of underlying basement faults as a result of the east - west crustal shortening which took place prior to, and then contemporaneous with the rise of the Zagros mountains (*cf.* Naqash and others, 1987; Boote and others, 1990; Hanna, 1990). Similar structural styles have been reported by many authors in the area such as Jabal Faiyah in the

Northern part of Oman mountains, the oil traps of the the Fahud and Natih in southern Oman (*cf.* Glennie, 1974) and the Rams Horst near Ras al Khaimah, U.A.E. (*cf.* Searle and others, 1983).

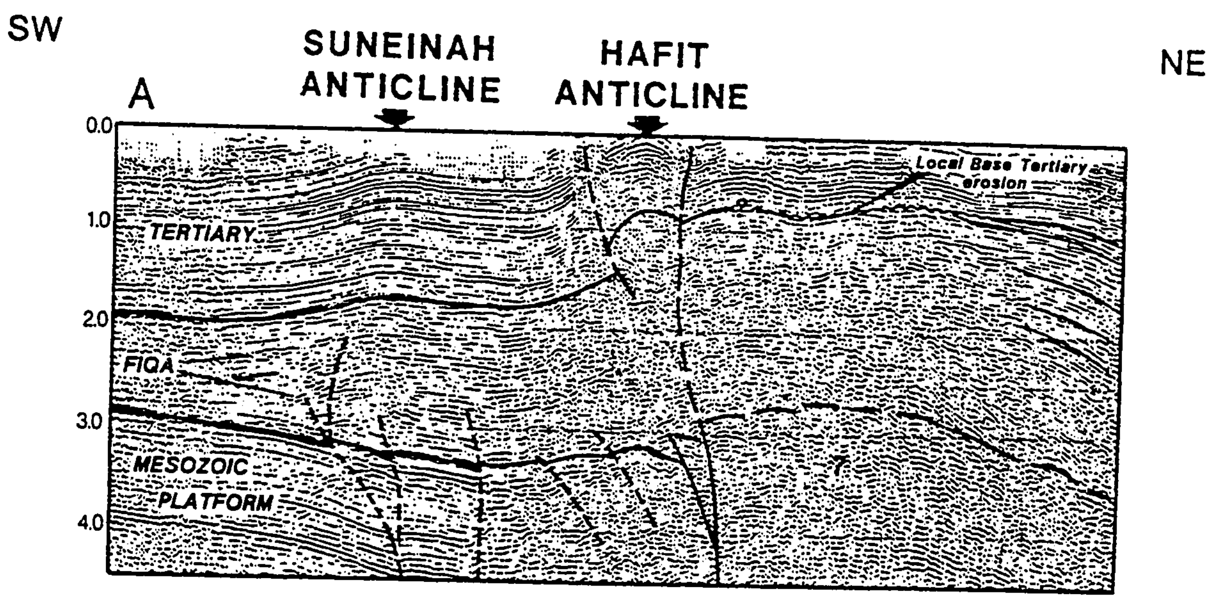


Fig.17 : A seismic section shot across Jabal Hafeet (From Boote and others, 1990).

VI. SUMMARY AND CONCLUSIONS

A total of 34 rock samples collected from the Late Paleogene succession of Jabal Hafeet were thin sectioned for stratigraphical and microfacies analysis. These have been examined under the microscope, and the following microfacies are defined from bottom to top:-

1- The Glauconitic, Peloidal, Nummulitic Marly Packstone / Wackestone Microfacies (Microfacies I):-

This microfacies represents the uppermost part of the Dammam *s.l.* Formation in the Jabal Hafeet section. It is proved to be of Late Eocene age. This part is usually missing in most of the Arabian Peninsula due to the Late Paleogene uplift and / or subsequent erosion. A rich nummulitic assemblage with *N.fabianii*, *N.striatus*, *N.retiatus*, *N. chavannesi*, *N.incrassatus* and *N. orbignyi* proves the Late Eocene age of this part of the Jabal Hafeet section, and equates it with the *N.fabianii s.s* and the *N.retiatus* Zones of Pomerol (1982).

Both the litho- and biofacies characteristics clearly correlate this microfacies with the bioclastic wackestone standard microfacies (SMF#9) of Wilson (1975) and the standard facies belt #2 (open sea shelf). Indeed, this part of the succession represents the base of a shallowing upward carbonate cycle, as the Late Paleogene sea was regressive off the largest part of the Arabian plate.

2- The Glauconitic, Dolomitic, Skeletal, Sandy, Wackestone Microfacies (Microfacies II):-

This microfacies represents the basal part of the Asmari Formation, which directly overlies the Dammam *s.l.* Formation in the studied section and is proved to be of Early Oligocene age. The unit is highly nummulitic, with abundant remains of *N.intermedius*, *N.vascus*, *N.bouillei* and *N. budensis.* which represent the main skeletal fragments and suggest an Early Oligocene age. These equate the present microfacies with the *N.intermedius* Zone of Pomerol (1982).

The Glauconitic, Dolomitic, Skeletal, Sandy Wackestone Microfacies is here interpreted to represent an open shelf condition of deposition on the basis of its marly nature but it could not be correlated directly with any of the standard microfacies of Wilson (1975).

3- The First Algal Floatstone Microfacies (Microfacies III):-

This microfacies follows Microfacies II conformably in the studied section, representing the lower part of the Asmari Formation. It contains abundant red calcareous algae (such as *Subterraniphyllum thomasi*) and benthonic Foraminiferids (such as the rotaliid *Victoriella sp.*) which suggest an Early Oligocene age. This microfacies represents a common reefal flank facies, with abundant skeletal debris which appear to have fallen down from upslope of the reef (forereef talus) and is here correlated with the Floatstone standard microfacies (SMF#5) of Wilson (1975) and the standard facies belt #4.

4- The Reefal Boundstone Microfacies (Microfacies IV):-

This microfacies represents the middle part of the Asmari Formation in the Jabal Hafeet section, and is considered to be of Early Oligocene age on the basis of its stratigraphic position (conformably overlying and underlying well-dated Early Oligocene successions). It clearly reflects organic reef build-ups at the platform margin and hence is correlated with the Boundstone standard microfacies (SMF#7) of Wilson (1975).

5- The Dolomitized, Peloidal, Nummulitic Packstone Microfacies (Microfacies V):-

This microfacies represents the upper part of the Asmari Formation in the studied section, which is truncated unconformably followed by the Miocene Lower Fars Formation. It is flooded with *N.intermedius*, *N.vascus*, *Heterostegina spp.*, *Operculina cf. complanatus*, and *Borelis spp.*, amidst a rich assemblage of both smaller and larger benthonic Foraminiferids. Such fossil assemblage confirms the Early Oligocene age of this microfacies and correlates it with the *N.intermedius* Zone of Pomerol (1982). Both its litho- and biofacies characteristics also equate this microfacies with the coquina, bioclastic grainstone standard microfacies (SMF#12) of Wilson (1975) which is usually found in back reef settings.

The Late Paleogene succession of Jabal Hafeet was also divided into the following assemblage biozones (from bottom to top):-

1- The *N.fabianii/N.retiatus* Zone of Late Eocene age.

2- The *N.intermedius/N.vascus/N.bouillei* Zone (of Early Oligocene age).

3- The *Subterraniphyllum thomasi* Zone (of Early Oligocene age).

4- The *Heterostegina - Borelis* Zone (of Early Oligocene age).

5- The *N.intermedius/N.vascus* Zone (of Early Oligocene age).

This analysis has revealed the following conclusions:-

1- Jabal Hafeet is the only outcrop in Arabia -so far- known with a definite, fossiliferous, marine, Late Eocene-Early Oligocene succession.

2- The succession represents a shallowing upward, carbonate cycle, moving from open sea shelf to shelf edge paleoenvironments, as the Late Paleogene sea was steadily receding off Arabia.

3- The Late Eocene part of the succession (Microfacies I) is here added to the Dammam Formation, which in its type section is only of Middle Eocene age. Consequently, A Dammam (*sensu lato*) Formation is suggested to cover the Middle-Late Eocene time in Arabia. The section in Jabal Hafeet is suggested here to be taken as a Reference Section for this expanded unit.

4- The Late Oligocene rocks are missing in the studied section which is truncated by the Oligocene-Miocene unconformity. However, such truncation could be a local event as the jabal Hafeet area had been subjected to several phases of folding, Faulting and jointing that resulted in the deformation of its sedimentary sequence. This was apparently connected with the Zagros Orogeny which had its climax in the Mio-Pliocene time (with another pulse during the Plio-Pleistocene). So, despite a world wide low sea stand during the Late Oligocene (Chattian) time, it is believed here that Late Oligocene sediments were deposited in the region and were subsequently eroded. This is evidenced by the presence of a more complete Asmari Limestone section in the subsurface of the U.A.E., further to the north. Nevertheless, the complicated, syndepositional structural evolution of the Jabal Hafeet area can suggest that the Late Oligocene part of the succession was not deposited at all, but the present study favors the first alternative.

5- The succession was found to be easily correlatable with previously suggested, well established rock units in the region such as the Dammam and Asmari Formations. Hence, local names that have recently been suggested for the studied section such as the Hafeet, Senayciah and Al-Jaww Formations are found to be superfluous and are dropped.

VII. REFERENCES

Adams, A.E.; Mackenzie, W.S.; Guilford, C. (1984): Atlas of Sedimentary Rocks under the Microscope; ELBS ed., Longman, 104 p.

Al-Furaih, A.A. (1983): Paleocene and Lower Eocene Ostracoda from the Umm er Radhuma Formation of Saudi Arabia; Univ. Kansas Paleo. Contr., paper 107, pp. 1-7.

Al-Naqib, K.M. (1967): Geology of the Arabian Peninsula, South western Iraq : U.S.G.S Prof. Paper 560-G, U.S. Government printing Off., Washington, 54 p.

Al-Sharhan, A.S. (1989): Petroleum Geology of the United Arab Emirates; Jour. Petro. Geol. v.12(3), pp. 253-288.

Al-Tamimi, M. (1985): Stratigraphical and Microfacies Analysis of the Early Paleogene succession in the Dammam Dome, Eastern Saudi Arabia. King Fahd Univ., Master's thesis.

Baker, N.E. and Henson, F.R.S. (1952): Geological conditions of Oil Occurance in Middle East fields; Am. Assoc. Petro. Geol., Bull., v.36, no. 10, pp. 1885-1901.

Beckmann, J.; Bolli, H.; Kleboth, P. and Decima, F.R. (1982): Micropaleontology and Biostratigraphy of the Campanian to Paleocene of the Monte Giglio, Bergamo Province, Italy; Momoire de Geologiche, Univerigta di Padora, pp. 91-172.

Bellen, R.C. van, Dunnington, H.V., Wetzel, R., and Morton, D.M. (1959): Iraq; Mesozoic and Paleozoic; Lexique Stratigraphique International, Vol. III, fasc. 10a, 333 p.

Beydoun, Z.R. (1988): The Middle East: Regional Geology and Petroleum Resources; Scientific Press, 292 p.

Beydoun, Z.R. and Greenwood J.E.G.W. (1968): Protectorat D'Aden et Dhufar; Lexique Stratigraphique International, Vol. III, fasc. 10b 2, 128 p.

Beydoun, Z.R. (1966): Geology of the Arabian Peninsula, Eastern Aden Protectorate and part of Dhufar; U.S.G.S Prof. Paper 560H; U.S. Government printing Off., Washington, 49 p.

Beydoun, Z.R. (1964): The Stratigraphy and Structure of the East Aden Protectorate; Report XXIst. Int. Geol. Cong. Copenhagen, part XXI, pp. 131-149.

Blondeau, A. (1972): Les Nummulites; Libraire Vuibert, Boulevard Saint-Germain, 63 Paris, (in french) 255 p.

Boles, G.C. & Franks, S.G. (1979): Clay diagenesis in Wilcox Sandstones of southwest Texas: Implications of smectite diagenesis on sandstone cementation; Jour. Sed. Petro., v.49, pp. 55-70.

Boote, D.R.D.; Mow, D. and Waite, R.I. (1990): Structural evolution of the Suneinch Foreland, Central Oman Mountains; In Robertson, A.H.F.; Searle, M.P. and Ries, A.C. (Eds.): Geology and Tectonics of the Oman Region; Geological Society, London, Special Publication, no.49, pp. 495-519.

Bozorgnia, F. and Banafti, S. (1964): Microfacies and micro-organisms of Paleozoic through Tertiary sediments of some parts of Iran; National Iranian Oil Company, Tehran, Iran, 158 pls., 22 p.

Brown, J.S. (1943): Suggested use of the word microfacies. Econ. Geol. 38, 325, New Haven.

Buday, T.(1980): The Regional Geology of Iraq, Vol. 1; Stratigraphy and Paleogeagraphy, I.I.M. Kassab and Jassim, (Eds.), State Organization for Minerals, Baghdad, 445 p.

Cherif, O.H. and El-Deeb, W.M.Z. (1984): The Middle Eocene - Oligocene of the Northern Hafit Area, South of Al-Ain City (United Arab Emirates); Geologic Mediterraneenne, Tome XI, no 2, PP. 207 a 217.

Cherif, O.H. and El-Deeb, W.M.Z. (1983a): Some Remarks on the Nummulites of the Hafit Area, Abu Dhabi, United Arab Emirates; Jour. U.A.E. Univ., Al-Ain, vol 1, 1983, pp. 117-134.

Cherif, O.H. and El-Deeb, W.M.Z. (1983b): An Oligocene Planktonic Foraminiferal assemblage from the Gabal Hafit area, south of Al-Ain, United Arab Emirates; Jour. U.A.E. Univ., Al-Ain, vol 1, 1983, pp. 169-178.

Clarke, M.W.H. (1988): Stratigraphy and rock unit nomenclature in the Oil producing Area of Interior Oman; Jour. of Petro. Geol. v.11(1), pp. 5-60.

Cuvillier, j. (1952): La notion de "microfacies" et ses applications. VIII Congr. Naz. Metano e Petrolio, sect.I, pp. 1-7.

Dunham, R.J. (1962): Classification of carbonate rocks according to depositional texture. In: W.E.Ham (Ed.), Classification of Carbonate rocks. Am. Assoc. Petro. Geol. Mem. no.1, pp. 108-121.

El-Naggar, Z. R. (1966): Stratigraphy and planktonic foraminifera of the Upper Cretaceous-Lower Tertiary succession in Esna-Idfu region, Nile valley, Egypt, U.A.R. Bull. Br. Mus. Nat. Hist., Supp. 2, 23 pls., 291 p.

El-Naggar, Z. R. (1967a): The occurrence of *Globorotalia inconstants* (Subbotina) in the type Heersian of Belgium, and the position of the Heersian in Paleocene stratigraphy. Rev. Micropaleont.10, pp. 97-106.

El-Naggar, Z. R. (1967b): Planktonic foraminifera of the Thanet Sands of England and the position of the Thanetian in Paleocene stratigraphy. J.Paleont.41, pp. 575-586

El-Naggar, Z. R. (1969): New suggestions for the division and correlation of Paleocene strata by the use of planktonic foraminifera. In Bronnimann, P. & Renz, H. H.(Eds.) Proc. first 1967.E. J. Brill, Leiden, pp. 182-201.

EL-Naggar, Z.R. and Dawood, A.M. (1979): Pre-historic life (In Arabic); Scientific Pub. House, Kuwait, 160 p.

El-Nakhal, H.A. and El-Naggar, Z.R. (1989): Review of the Biostratigraphy of the Hasa Group (Paleogene) in Saudi Arabia, Kuwait and Adjacent Regions; Jour. King Saud Univ., Vol.1, Sciences (1,2), pp. 73-99.

Ellis, B.F. and Messina, A.R. (1966): Catalogue of Index Foraminifera; special publication, volume 2, the Amer. Mus. Nat. Hist., New York.

El-Khayal, A.M. (1974b): Foraminiferal biostratigraphy of the Umm er Radhuma Formation (Paleocene-Lower Eocene) of Eastern Saudi Arabia; Bull. Fac. Sci., Riyadh Univ., pp. 195-213.

El-Khayal, A.M. (1974c): Some New Species of Large Foraminifera from the Paleocene of Saudi Arabia and the origin of Discocyclina; Bull. Fac. Sci., Riaydh Univ., pp. 215-222.

Embry, A.F. and Klovan, J.E. (1971): A Late Devonian reef tract on northeast Banks Island, North-west Territories. Can. Petrol. Geol. Bull.,19, pp. 730-781.

Flugel, E. (1982): Microfacies Analysis of Limestone; Springer-Verlag, Berlin - Heidelberg - New York, 633 p.

Flugel, E. (1972): Mikrofazielle Untersuchungen in der Alpinen Triassic - Metoden und Probleme. Mitt. Ges. Geol. Bergbaustud, 21, pp. 9-64.

Folk, R.L. (1962): Special Subdivision of Limestone Types, in Ham, W.E. (Ed.), Classification of Carbonate rocks; Am. Assoc. Petro. Geol. Mem. no.1, pp. 62-84.

Gignoux, M. (1955): Stratigraphical Geology; San Francisco, W.H. Freeman and Co., pp. 235

Glennie, K.W., M.G.A Beuf, M.W. Hughes Clark, M. Moody-Stuart, W.F.H. Pillar and Reinhardt, B.M. (1974): The Geology of the Oman Mountains: Verhandelingen van het Koninklijk Nederlands geologish mijnbouwkundig Genootschap, 31, 423 p.

Goodwell, H.G.& Garman, R.K. (1969): Carbonate geochemistry of Superior deep testwell, Andros Island, Bahamas; Am. Assoc. Petro. Geol. Bull., v.53, no. 4, pp. 513-536.

Hanna, S.S.(1990): The Alpine deformation of the Central Oman Mountains; In

Robertson, A.H.F.; Searle, M.P. and Ries, A.C. (Eds.) Geology and Tectonics of the Oman Region; Geological Society, London, Special Publication, no.49, pp. 341-359.

Harris and Forest (1984): Middle Cretaceous Carbonate Reservoirs, Fahud Field and Northwestern Oman; Am. Assoc. Petro. Geol. Bull., v.68, no.5, pp. 649-658.

Hasson, P.(1982): Studies in Cenozoic biostratigraphy based on microplankton; Section IV: Biostratigraphy of the Umm Al-Radhuma Formation of the Rub'al Khali Basin. Princeton Univ., unpublished thesis, Univ. Microfilms internat., Ann Arbor, MI. Ref.no.8305902

Hasson, P.(1985): New observations on the biostratigraphy of the Saudi Arabian Umm Al-Radhuma Formation (Paleogene) and its correlation with neighboring regions. Micropaleontology, v.31, no.4, pp. 335-364.

Haynes, J.R.(1981): Foraminifera; Macmillan Publishers LTD., 433 p.

Henson, F.R.S. (1950): Cretaceous and Tertiary Reef Formations and associated sediments in Middle East; Am. Assoc. Petro. Geol. Bull. Bull., v.34, no.2, pp. 215-238.

Horowitz, A.S. and Potter, P.E. (1971): Introductory Petrography of Fossils; Springer-Verlag, 100 pls, 302 p.

James, G.A. and Wynd, J.G. (1965): Stratigraphic Nomenclature of Iranian Oil Consortium Agreement Area; Am. Assoc. Petro. Bull., v.49, no___, pp. 2182-2245.

Kamel, S. (1985): Stratigraphical and Microfacies Analysis of the Late Cretaceous Early-Paleogene Phosphate-bearing Succession in Turayf Area, Saudi Arabia. King Fahd Univ., Master's thesis.

Kamen-Kaye, M. (1970): Geology and Productivity of the Persian Gulf Synclinorium: Am. Assoc. Petro. Geol. Bull., v.54, no.12, pp.2371-2394.

Kashfi, M.S (1976): Plate Tectonics and Structural Evolution of the Zagros geosyncline, southwestern Iran. Geol. Soc. Am. Bull. v.87, p. 1486 - 1490.

Kendall, C.G. and Schlager, W. (1981): Carbonates and Relative Changes in Sea Level; Marine Geology, 44(1981), pp. 181-212.

Koop, W.J. and Stoneley, R. (1982): Subsidence history of the Middle East Zagros Basin, Permian to Recent: Phil. Trans. Roy. Soc. London, A305, p.149-168.

Lewis, D.W. (1984): Practical Sedimentology; Hutchinson Ross Publication Co., 229 p.

Loeblich, A.R. and Tappan, H. (1988): Foraminiferal Genera and their classification; Van Nostrand Reinhold Co. New York. 847 pls., 970 p.

Majewske, O.P. (1969): Recognition of invertebrate fossil fragments in rocks and thin sections : E.J. Brill, Leiden, Pls. 106, 101 p.

Mattes, D.H. & Mountjoy, E.W. (1980): Burial dolomitization of the Upper Devonian Miette buildup, Jaspar National Park, Alberta. In: Zenger, D.H., Dunham, J.B. and Ethington, R.L.(Eds.), Concepts and Models of Dolomitization; Spec. Publ. Soc. econ. Paleont. Miner., 28, pp. 259-297.

McHargue, T.R. & Price, R.C. (1982): Dolomite from clay in argillaceous or shale - associated marine carbonates; Jour. Sed. Petrol., v.52, pp. 873-886.

McKenzie, J.A. (1981): Holocene dolomitization of calcium carbonate sediments from the coastal sabkha, Abu Dhabi, U.A.E., and it's relation to evaporative dolomite genesis. In: Zenger, D.H., Dunham, J.B. and Ethington, R.L.(Eds.), Concepts and Models of Dolomitization; Spec. Publ. Soc. Econ. Paleont. Miner., 28, pp. 259-297.

Milton, D.I. (1967): Geology of the Arabian Peninsula, Kuwait; U.S. Geol. Survey Prof. Paper 560-F, 7 p.

Morris, R.W. (1960): Paleocene-Eocene Paleontologic Correlation; Project 13, final report, ARAMCO, New York.

Murris, R.J. (1980): Middle East: Stratigraphic Evolution and Oil Habitat. Am. Assoc. Petro. Geol. Bull., v.64, no.5, p.597-618.

Naqash, A.B.; Sherif, O.H. and Hancock, P.L. (1987): The Geology of the Zagros-style fold near Al-Ain, Southeast margin of the Arabian Platform; Iraqi J. Sci., v.28, nos. 3 & 4, pp. 471-482.

Nolan, S.C.; Skelton, P.W.; Clissold, B.P. and Smewing, J.D. (1990): Maastrichtian to Early Tertiary stratigraphy and paleogeography of the Central and Northern Oman Mountains; In Robertson, A.H.F.; Searle, M.P. and Ries, A.C.(Eds.): Geology and Tectonics of the Oman Region; Geological Society, London, Special Publication, no.49, pp. 495-519.

North American Commission on Stratigraphic Nomenclature (1983): North American Stratigraphic Code : Appendix in Boggs, S.(1987): Principles of Sedimentology and Stratigraphy; Merril Pub. Co. 784 p.

Owen, R.M. and Nasr, S.M. (1958): Stratigraphy of the Kuwait - Basra area, in L.G.Weeks (Ed.), Habitat of Oil; Am. Assoc. Petro. Geol. Symposium, June. 1958, pp.1252-1278.

Page, R. (1959): Paleontological correlation of the Paleocene-Eocene rocks; Progress Report Project XIII, ARAMCO, New York.

Patton, T.L. and O'Connor, S.J. (1988): Cretaceous Flexural History of Northern Oman Mountain Foredeep, United Arab Emirates; Am. Assoc. Petro. Geol. Bull., v.72, no.7, pp. 797-809.

Pearce, J.A., Alabaster, T., Shelton, A.W. & Searle, M.P. (1981): The Oman ophiolite as a Cretaceous arc-basin complex: evidence and implications; Philosophoical Transactions of the Royal Society of London, A3, pp. 299-317.

Pilgrim, G.E. (1908): The geology of Persian Gulf and the adjoining portions of Persia and Arabia.Mem.geol.surv. India XXXIV, part 4, IV + IV + IV177 pp.

Pinnington, D.J. (1981): United Arab Emirates/Qatar; in Well Evaluation Conference, Schlumberger publications, pp. 1-32.

Pomerol, C. (1982): The Cenozoic Era, Tertiary and Quaternary; Ellis Horwood Series in Geology, Ellis Horwood limited publishers, Chichester, 272 p.

Powers, R.W. (1968): Lexique Stratigraphic International, Vol.III, Asie, Fasc. Lob 1, Arabie Saoudite: Geol. Congr. Comm. Stratigr., Centre Nat, Recherche, Paris, 177 p.

Powers, R.W., L.F. Ramirez, C.D. Redmond and Elberg, E.L. (1966): Geology of the Arabian Peninsula, Sedimentary Geology of Saudi Arabia. U.S. Geol. Survey Prof. Paper 560-D, 147 p.

Robertson, A.H.F. (1987a): The transition from a passive margin to an Upper Cretaceous foreland basin related to ophiolite emplacement in the Oman Mountains; Geol. Soc. Amer. Bull., v.99, pp. 633-653.

Sampo, M. (1969): Microfacies and microfossils of the Zagros area, Southwestern Iran (from pre-Permian to Miocene): E.J.Brill, Leiden, 105 pls., 102 pp.

Sander, N.J. (1962): Apercu Paleontologique et Stratigraphique de Paleogene en Arabie Seoudite Orientale; Rev. de Micropaleontologie, v.5, no.1, pp. 3-40.

Sartorio, D. and Venturini, J.(1988): Southern Tethys Biofacies; Agip S.p.A., 230 p.

Scholle, P.A. (1978): A Color Illustrated Guide To Carbonate Rock Constituents, Textures, Cements, and Porosities; Am. Assoc. Petro. Geol. Memoir 27, 241 p.

Scholle, P.A., Bebout, D.G. and Moore, C.H.(1983): Carbonate Depositional Environments (Eds.); Am. Assoc. Petro. Geol. Mem. 33, 708 p.

Scoffin, T.P.(1987): An Introduction to Carbonate Sediments and Rocks; Blackie and Son Ltd, 274 p.

Searle, M.P., James, N.P., Calon, T.J. & Smewing, J.D. (1983): Sedimentological and structural evolution of the Arabian continental margin in the Musandam Mountains and Dibba Zone, United Atab

Emirates; Geol. Soc. Amr. Bull., v.94, pp. 1381-1400.

Smout, A.H. (1954): Lower Tertiary Foraminifera of the Qatar Peninsula; London, Jarrold and Sons, Ltd, 96 p.

Steincke, M., R.A. Bramkamp and Sander N.J. (1958): Stratigraphic relations of Arabian Jurassic oil; Habitat of Oil, Am. Assoc. Petro. Geol. Symposium, pp.1294-1329.

Steincke, M. and Bramkamp, R.A. (1952): Mesozoic Rocks of Eastern Saudi Arabia (Abs.); Am. Assoc. Petro. Geol. Bull., v.6, no.5, p.909.

Stockmal, G.S, Beaumont, C. and Boutilier, R. (1986): Geodynamic models of convergent tectonics: the transition from rifted margin to overthrust belt and consequences of foreland basin development; Am. Assoc. Petro. Geol. Bull., v.70, pp. 181-190.

Sugden, W. and Standring, A.J. (1975): Qatar Peninsula, Lexique Stratigraphique International; Centre National de la Recherche Sci., Paris, Vol. III, Fascicule 10b3, 120 p.

Thomas, A.N. (1950): The Asmari Limestone of South-West Iran; A reprint from the International Geological Congress "Report of the Eighteenth Session, Great Britain," Part VI, pp. 35-44.

Thralls, W.H., and Hasson, R.C. (1956): Geology and oil resources of eastern Saudi Arabia. Symposium Sobre Yacimientos de Petroleo Y Gas. 20th Intern. Geol. Congr., Mexico, 1, pp.9-32.

Tleel, J.W. (1973): Surface geology of Dammam Dome, Eastern Province, Saudi Arabia; Am. Assoc. Petro. Geol. Bull., v.57, pp. 558-576.

Tucker, M.E. and Wright, V.P. (1990): Carbonate Sedimentology; Blackwell Scientific Publications, 482 p.

Tucker, M.E. (1981): Sedimentary Petrology, An Introduction; Blackwell Scientific Publications, 252 p.

Vail, P.R. and Mitchum, jr., R.M. (1977): Seismic Stratigraphy and Global Changes of Sea Level, Part 1; Overview, in Payton, C.E. (Ed.), Seismic Stratigraphy - Application to Hydrocarbon exploration; Am. Assoc. Petro. Geol. Mem. 26, pp. 51-52.

Vail, P.R. and Mitchum, jr., R.M.(1977): Seismic Stratigraphy and Global Changes of Sea Level, Part 1; Global Cycles of relative Changes of Sea level, in Payton, C.E.(Ed.): Seismic Stratigraphy- Application to Hydrocarbon exploration; Am. Assoc. Petro. Geol. Mem. 26, pp. 83-97.

Wasimuddin, M. (1985):Stratigraphical and Microfacies Analyses of The Late Cretaceous/Early Palaeogene Phosphate-bearing Succession in the Northern Saudi Arabia (Thanyat Turayf Areas), M.S. Thesis. University of Petroleum and Minerals Dhahran , Saudi Arabia.

Willis, R.P. (1967): Geology of the Arabian Peninsula. Bahrain. U.S.G.S. Prof. Paper 560-E, 4 p.

Wilson, J.L. (1975): Carbonate facies in geologic history. Springer-Verlag, New York, 469 p.

Wilson, J.L. (1974): Characteristics of carbonate platform margins; Am. Assoc. Petro. Geol. Bull., v.58, pp. 810-828.

THE MICROFACIES PLATES (1-22)

PLATE 1

The Dammam Formation

The Glauconitic, Peloidal, Nummulitic Marly Packstone / Wackestone Microfacies; (Microfacies I)

Figs.1-16 : Photomicrographs showing random sections in Foraminiferid remains embedded in a micritic matrix that is partially recrystallized into micro- to pseudosparite (fig.16), including miliolid remains (1,2,5,6,7), *Dictyoconus sp.* (3), *Orbitolites sp.* (1,4), Fusarchaias spp. (5), *Praerhapydionina sp.*, (1,2,5), *Rhapydionina sp.*, (8), Nummulitic remains (2,7,9,11,13,14), *Nummulites fabianii* (Prever),1905 (7,9,,10,11), *N. retiatus* Raveoda, 1959, form A (14), bryozoan remains (14,15), and *Turborotalia centralis* (Cuchman & Bermudez, 1937), (10,11,12). All P.P. light X35 except 11 C.N. X35 and 12 C.N. X140.

PLATE 1

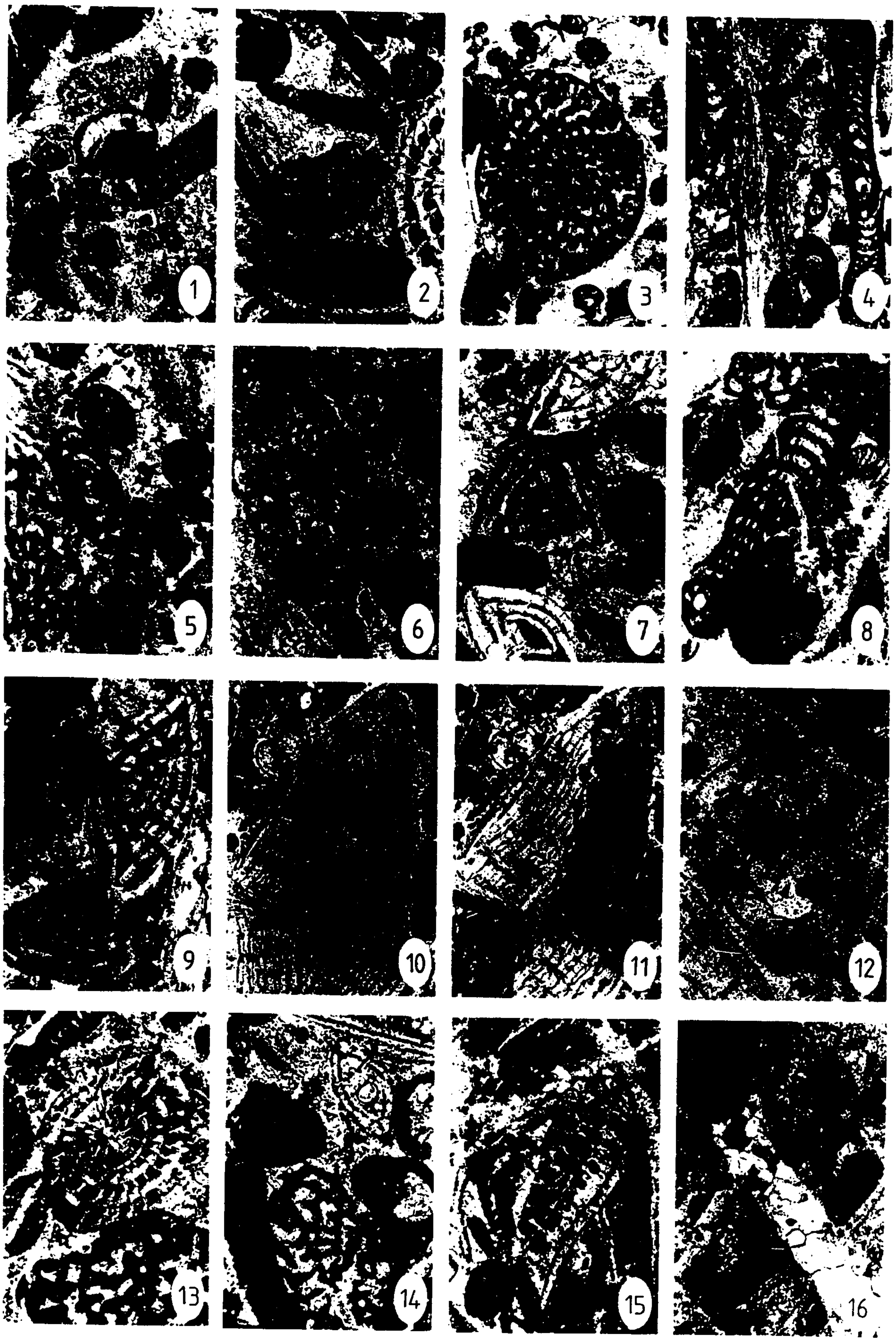


PLATE 2

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing the peloidal, skeletal, packstone-wackestone nature of the microfacies with recrystallized micritic matrix. They also showing *Rotalia sp.* (1,11); *Pyrgo sp.* (1,6), *Triloculina sp.* (2), *Quinquloculina sp.* (2,3,9,15,16), *Nummulites chavannesi* De La Harpe, 1878, form A, (9,10), *N. fabianii* (Prever), 1905, form B, (3), *N. retiatus* Raveoda, 1959, form A (7), *Praerhapydionina sp.* (2), *Turborotalia centralis* (Cuchman & Bermudez, 1937), (4), *Guttulina sp.*, (5,6,7), ostracod carapace (14) and echinodermal and bryozoan remains (8, 13-16). All are P.P. light X35 except 8,10,13,16 C.N. X35.

PLATE 2

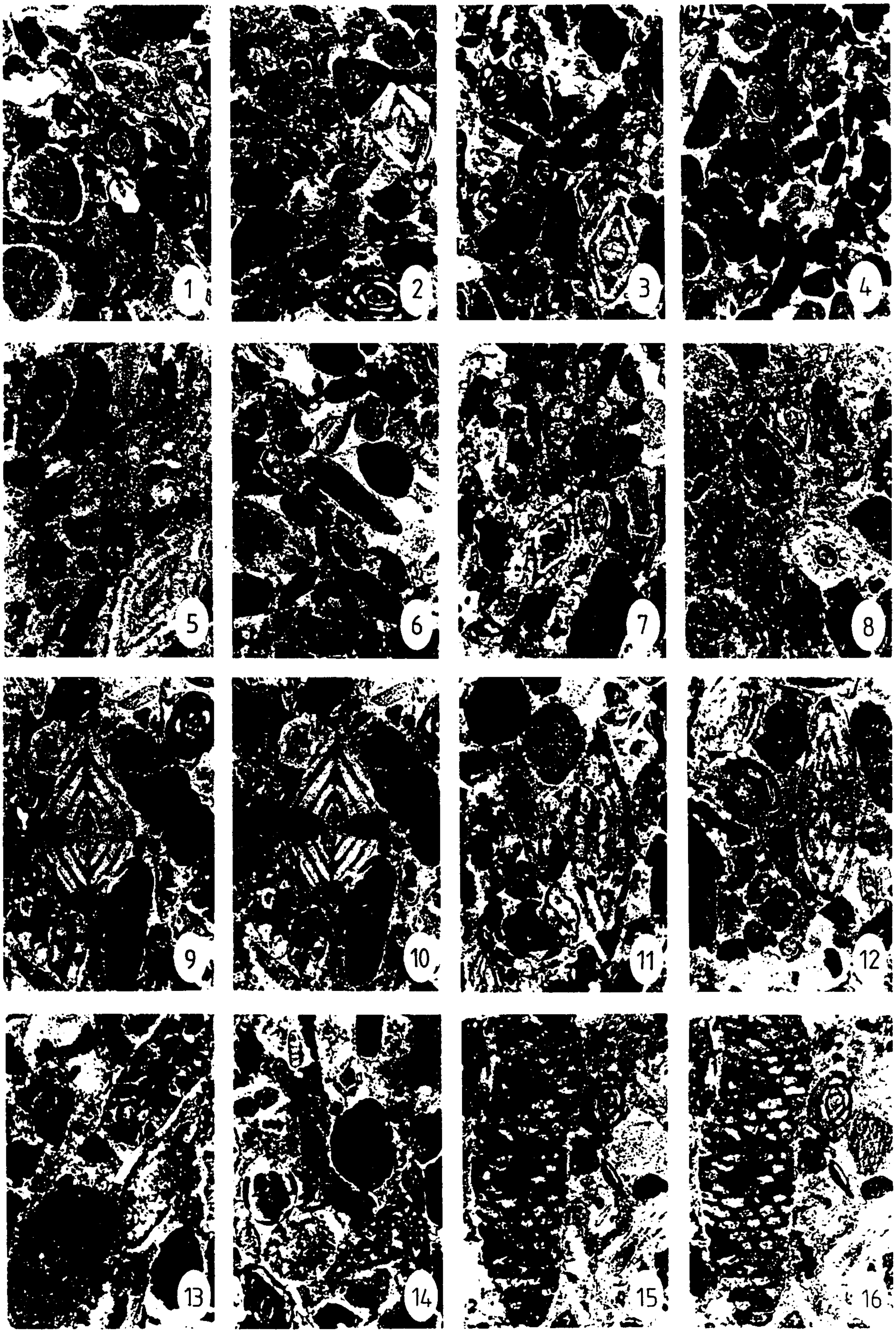


PLATE 3

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing random sections in Nummulitic, Rotaliid and Polymorphinid Foraminiferid remains embedded in a partially recrystallized micritic matrix including *Nummulites fabianii* (Prever), 1905, form B, (1-4), *Nummulites retiatus* Raveoda, 1959, form B, (5-12), *Nummulites retiatus* Raveoda, 1959, form A, (13,14) and *N. incrassatus* De La Harpe, 1883, form B, (15,16). All P.P. light X35 except 2,4,7,8,10,12,14,16 C.N. X35

PLATE 3

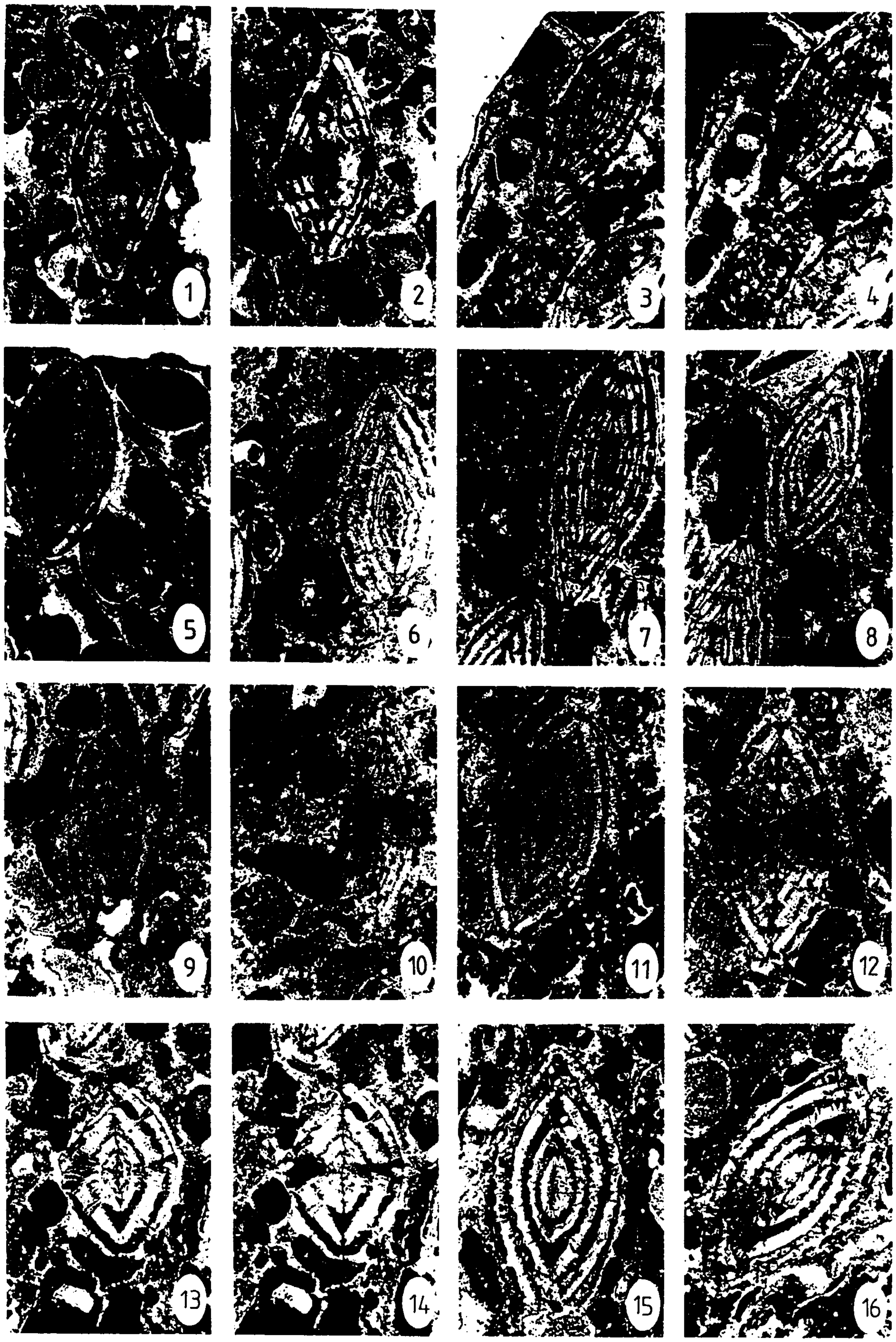


PLATE 4

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing the peloidal, skeletal, packstone-wackestone nature of the microfacies with recrystallized micritic matrix. They also showing *Rotalia sp.* (1,3,4);

Guttulina sp. (4), Miliolid remains (2,3), *Nummulites chavannesi* De La Harpe, 1878, form B, (5), *N. retiatus* Raveoda, 1959, form A (6,7), *N. incrassatus* De La Harpe, 1883, form B, (8), *N. orbignyi* (Galeotti), 1837, form B, (9,10), *Heterostegina sp. cf. H. papyracea* (11), *Operculina sp.* (12) and *Spiroclypeus sp.* (13-16). All are P.P. light X35 except 2,5,10,14,16 C.N. X35.

PLATE 4

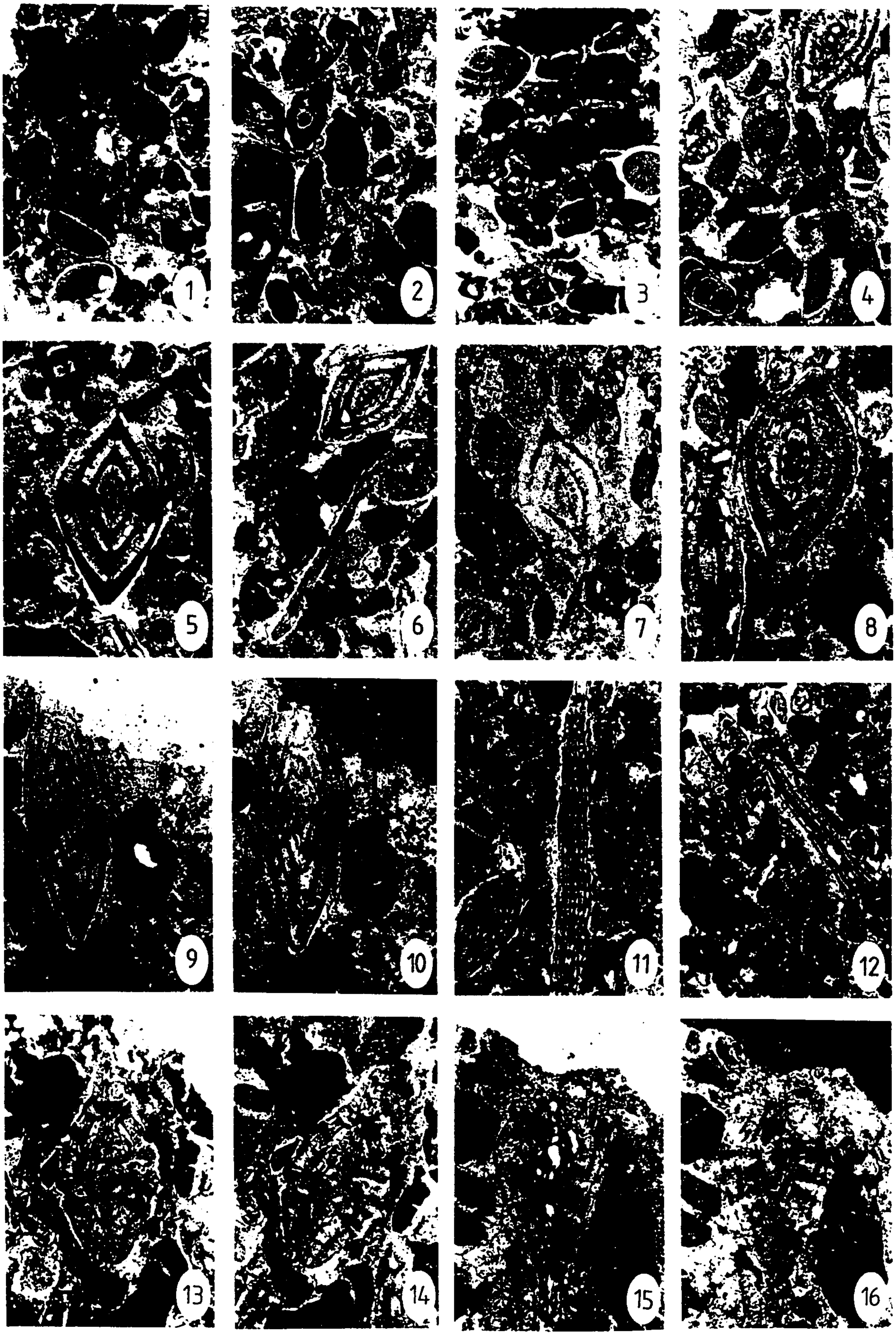


PLATE 5

The Dammam Formation

Microfacies I (cont.)

Figs.1-16 : Photomicrographs showing axial and oblique sections in Nummulitic, Rotaliid and Miliolid Foraminiferid as well as echinodermal and bryozoan remains in a partially recrystallized, slightly iron-stained, micritic matrix, including *Nummulites retiatus* Raveoda, 1959, form B (1-12,14-16), *N. fabianii* (Prever), 1905, form B (16), *Rotalia sp.* (7,9,10,12), *Praerhapydionina sp.* (11,13), *Guttulina sp.* (14), Echinodermal plates and spines (3,4,6,14) and bryozoan remains (7,12). All are P.P light X35.

PLATE 5

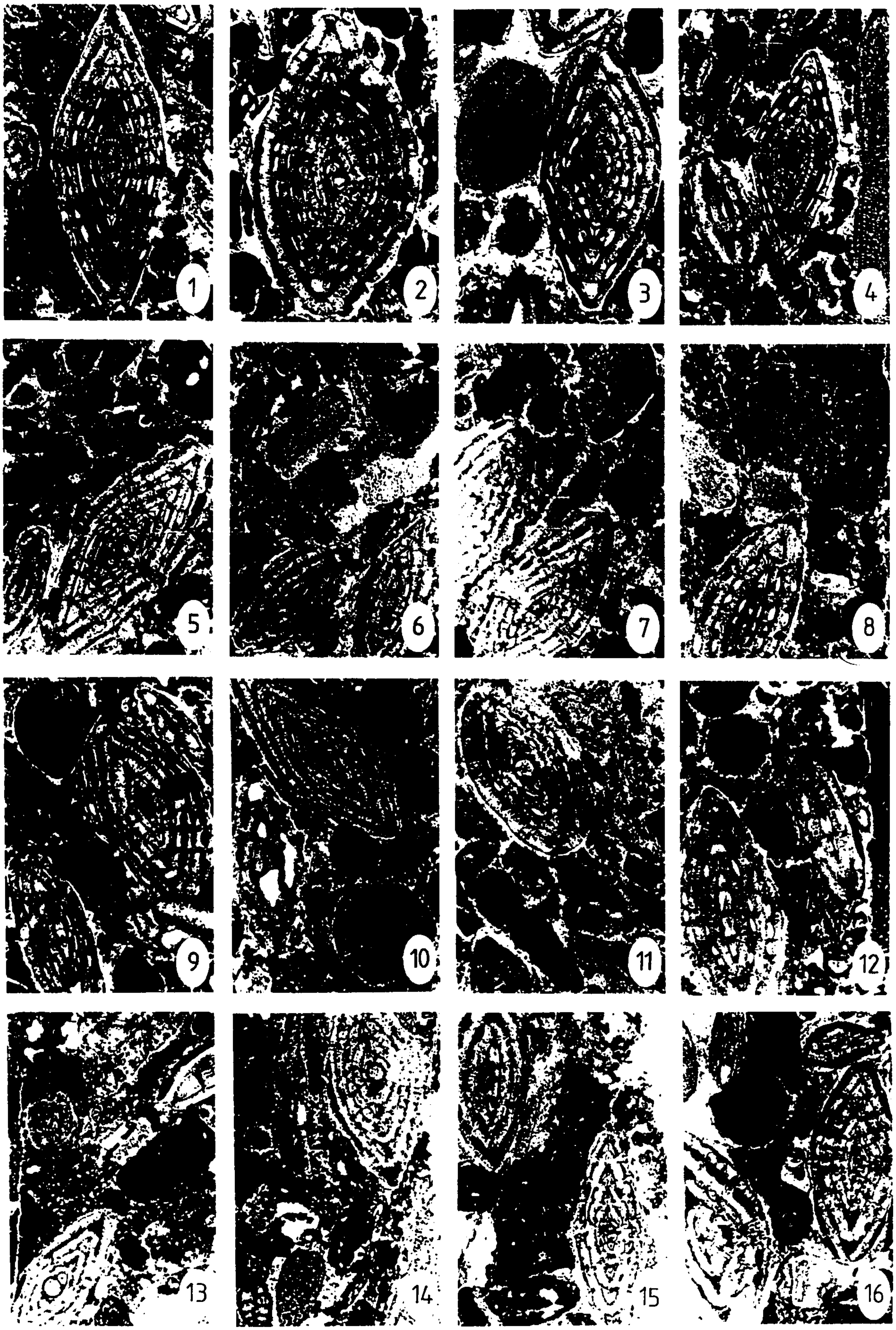


PLATE 6

The Dammam Formation

Microfacies I (cont.)

Figs.1-16 : Photomicrographs showing random sections in Rotaliid, Miliolid, Discocyclinid, and Globigerinid Foraminiferid, algal as well as bryozoan remains embedded in a partially recrystallized micritic matrix, including *Discocyclina sp.* (1), *Orbitolites sp.* (2), *Rotalia sp.* (2,5,8), *Rhapydionina sp.* (4,5,6,), *Praerhapydionina sp.* , axial sections, (11,12) and an equatorial section, (13). *Fusarchaias operculiniformis* Henson, 1944, (9,10), *Quinquloculina sp.* (7), *Dendritina sp.* (16), *Globigerinatheka sp.* (15) and bryozoan and algal remains (13,14). Batches of the original micritic matrix can be observed in fig.13. All P.P light X35 except 12 C.N. and 15,16 C.N. X140.

PLATE 6

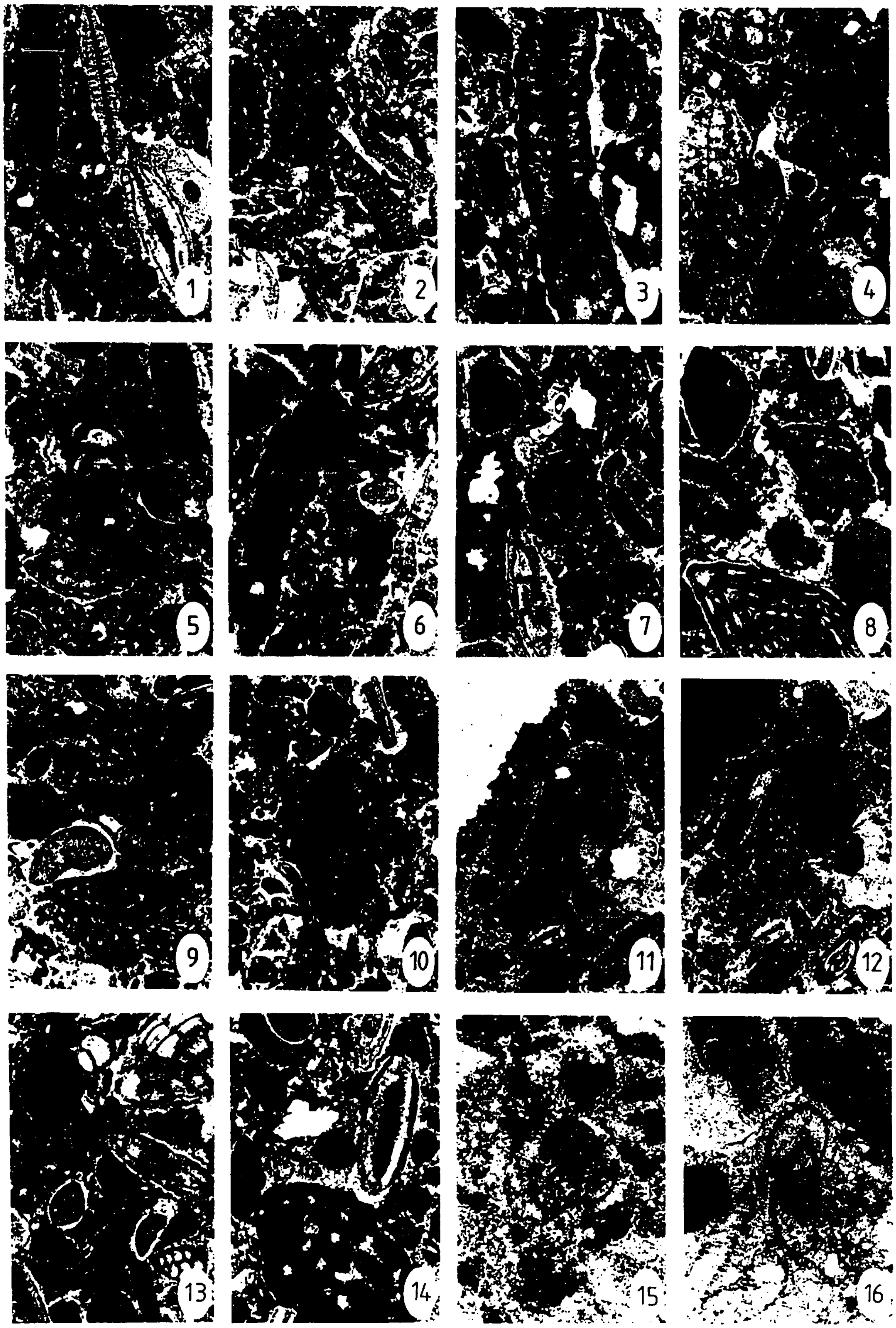


PLATE 7

The Dammam Formation

Microfacies I (cont.)

Figs.1-16 : Photomicrographs showing random sections in Nummulitic, Miliolid, Rotaliid Foraminiferid and bryozoan remains embedded in a highly packed, partially recrystallized micritic matrix. These remains include *Rotalia sp.* (1,2) *Pyrgo sp.* (3), *Peneroplis sp.* (4), *Praerhapydionina delicata* Henson, 1944, (4) *Spirolina austriaca* d'Orbigny, (5,6) *Fusarchaias operculiniformis* Henson, equatorial sections, (15,16), *Nummulites striatus* (Bruguiere), 1792, (9,10), *Nummulites retiatus* Roveda, 1959, axial sections (11,12), equatorial sections (13,14), bryozoan and echinodermal remains and intraclasts (1,2,4,5,7,8). All are P.P. light X35 except 6 X140 and 2,12 C.N. X35).

PLATE 7

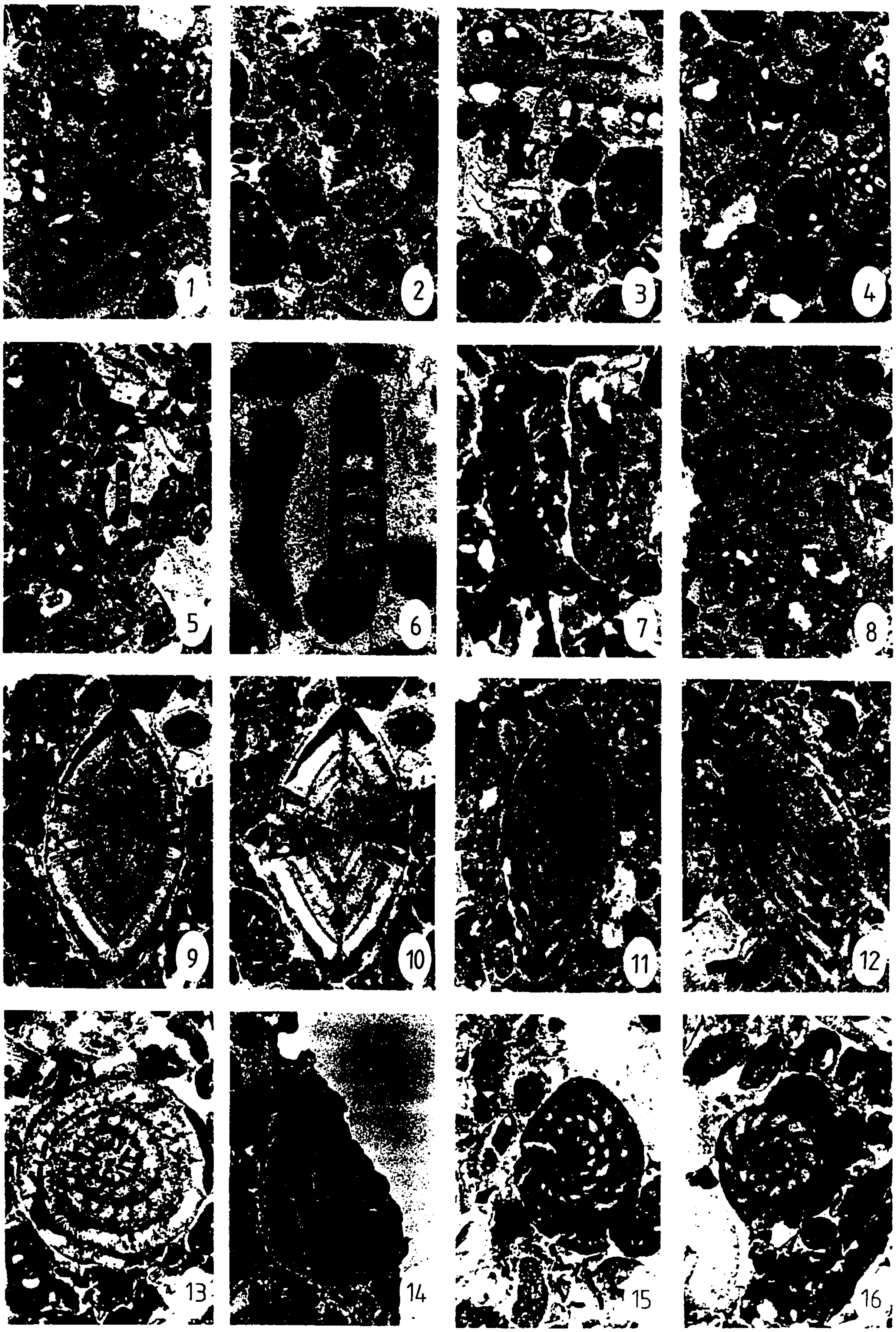


PLATE 8

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing random sections in Nummulitic, Miliolid and Rotaliid Foraminiferid remains embedded in a partially recrystallized micritic matrix. These remains include *Nummulites retiatus* Raveoda, 1959, form B (5-10), form A (11,12). *N. chavannesi* De La Harpe, 1878, (13,14), *Discocyclina sp.* (16), *Praerhapydionina delicata* Henson, (3), *Praerhapydionina sp.* (1,9,13), *Fusarchaias sp.* (11), *Rotalia sp.* (6,8,12), peloids and intraclasts (1,2,4). P.P. light, X35 except 2,11,15 C.N.

PLATE 8

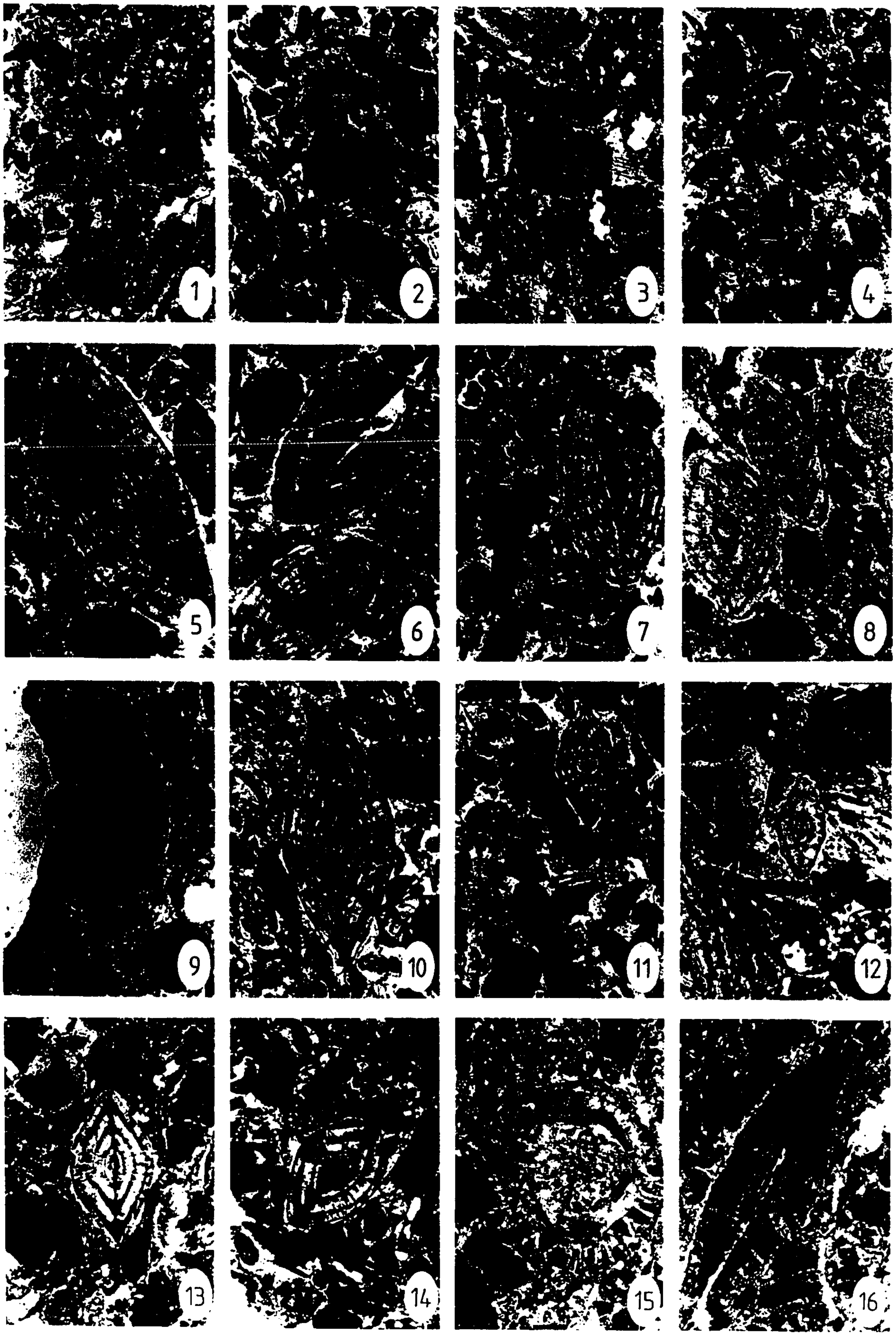


PLATE 9

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing random sections in Nummulitic, Chapmaninid, Globorotaliid and Miliolid Foraminiferid, echinodermal and bryozoan remains embedded in a partially recrystallized micritic matrix. These remains include *Operculina sp.* (1), *Heterostegina sp.* (2), *Spiroclypeus sp.* (3,4), *Praerhapydionina delicata* Henson, (10), *Praerhapydionina sp.* (5,6), *Chapmanina sp.* (12), *Turborotalia centralis* (Cuchman & Bermudez, 1937), (13,14), bryozoan remains (1,7,8,9,11), echinodermal spines and plates (7,8) and an extraclast (15,16). All P.P. light, X35 except 2,4,6,9,16 C.N.; 13 X140 and 12 C.N., X140.

PLATE 9

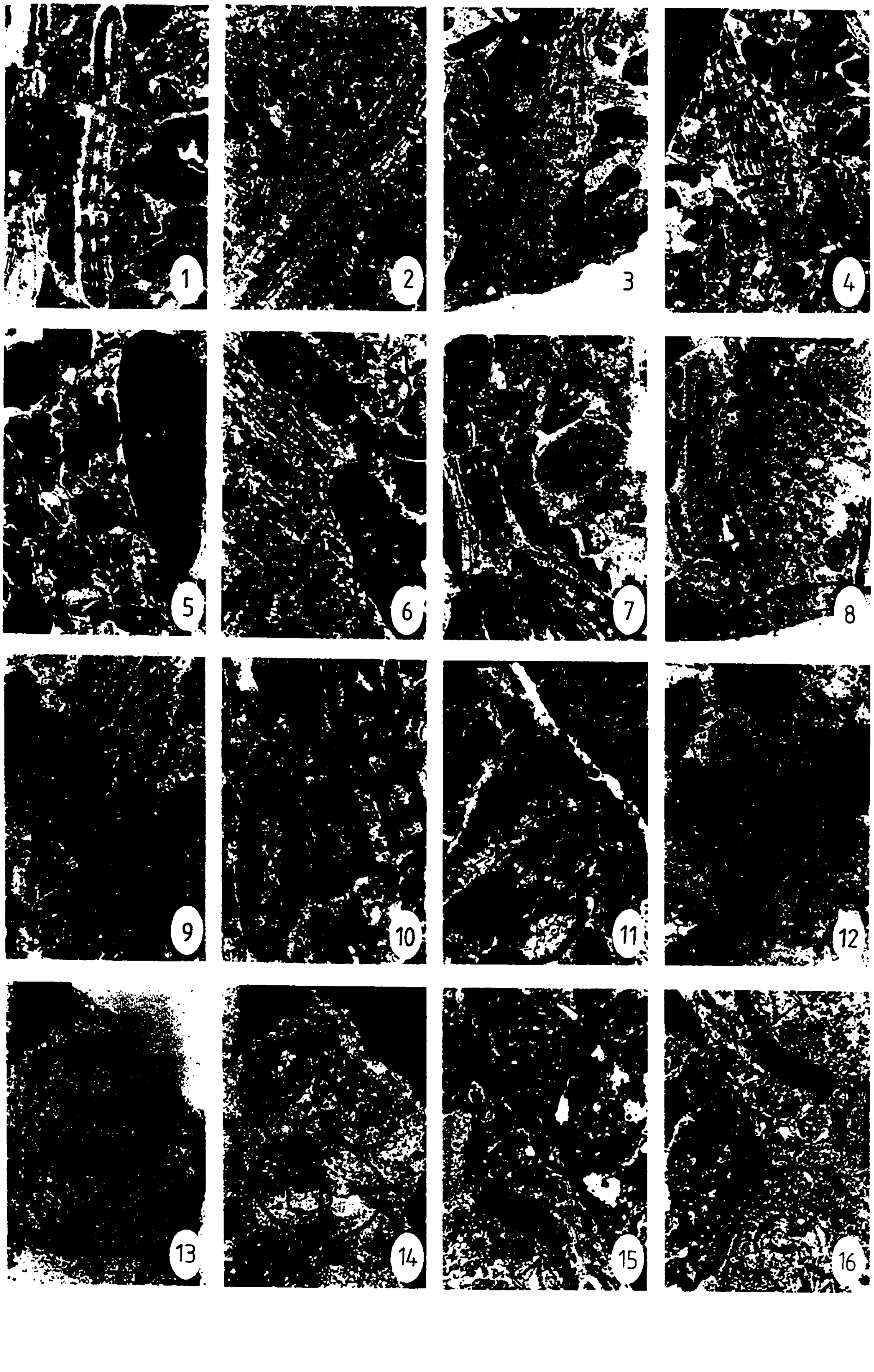


PLATE 10

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing random sections in Nummulitic, Rotaliid, Polymorphinid and Miliolid Foraminiferid, algal and bryozoan remains in a partially recrystallized micritic matrix. These remains include *Nummulites retiatus* Raveoda, 1959, (9,10), *N. striatus* (Bruguiere), 1792, (11), *Discocyclina sp.* (12), *Turborotalia centralis* (Cuchman & Bermudez, 1937), (4,15,16), *Guttulina sp.* (1,2,4), *Quinquloculina spp.* (1,3,5), *Praerhapydionina sp.* (7,8) *Rotalia sp* (4,8,9,16), *Lithothamnium sp.* (5,6), bryozoan remains (14,15) and extraclasts (13). The micritic matrix is still relatively preserved (e.g.1,2,3,11,15). All P.P. light, X35 except 2,4,7,8 C.N. and 6 C.N., X140.

PLATE 10

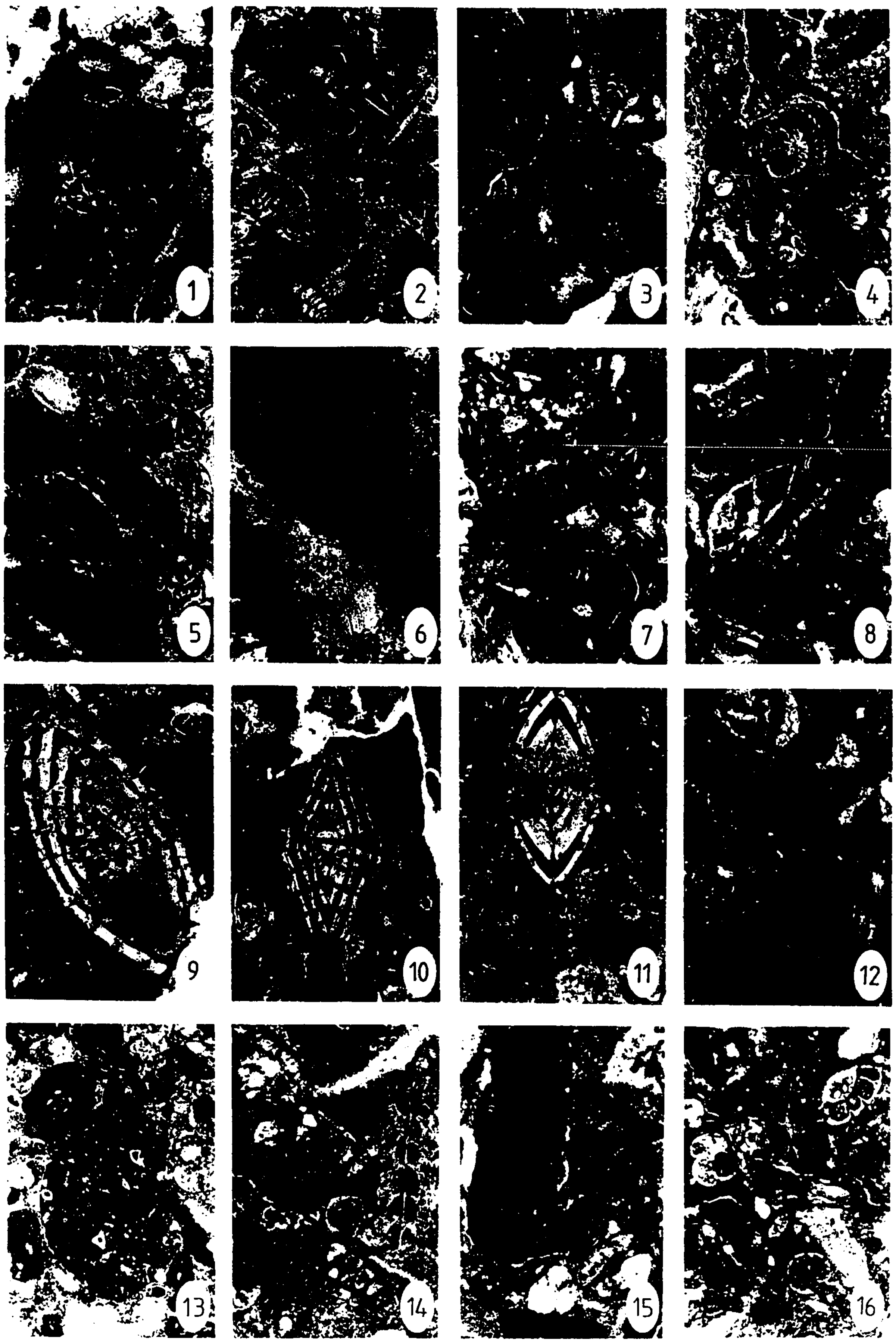


PLATE 11

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing the peloidal, skeletal packstone - wackestone nature of the microfacies. They are also showing Nodosariid (2,3), *Pyrgo sp.* (2,6), *Quinquloculina sp.* (6), *Dictyoconus sp.* (13), *Rotalia sp.* (3), *Heterostegina sp.* (4,9,10), *Operculina sp.* (11,12), *Nummulites spp.* (4,7,10,12,15), *Discocyclina sp* (14), echinodermal and bryozoan remains (10,15,16), peloids (1,5) and intraclasts (8,14). All P.P. light, X35 except 7 C.N.

PLATE 11

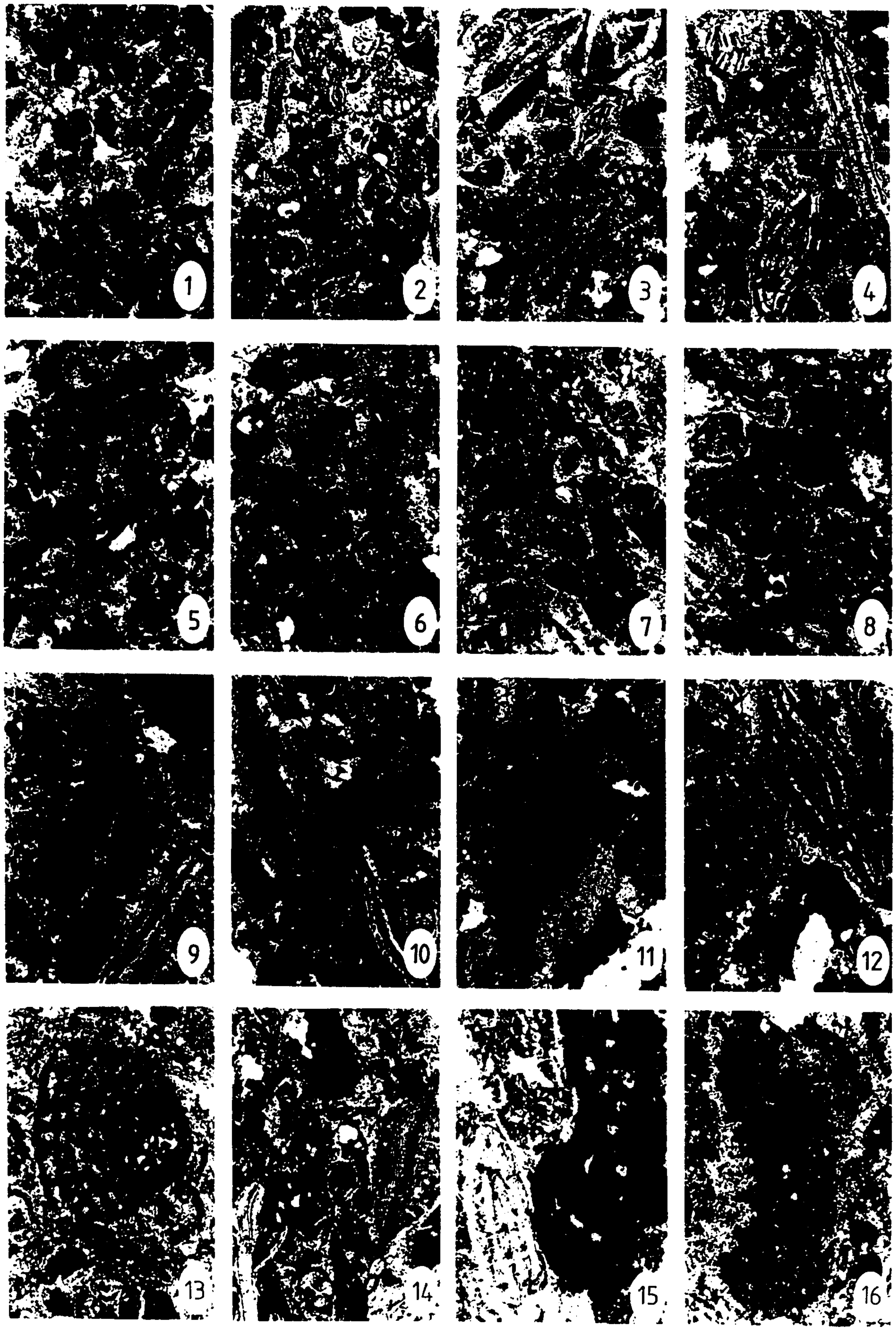


PLATE 12

The Dammam Formation

Microfacies I (cont.)

Figs.1-16 : Photomicrographs showing random sections in Nummulitic, Rotaliid Foraminiferid, echinodermal, algal and bryozoan remains embedded in a partially recrystallized, micritic matrix. These remains include *N. retiatus* Raveoda, 1959, form B, (1-11); form A, (12,14), *N. sp. cf. N. incrassatus* De La Harpe, 1883 (15,16), bryozoan remains (7,10,11,14), algal remains (13) and echinodermal remains (15). All P.P. light, X35.

PLATE 12

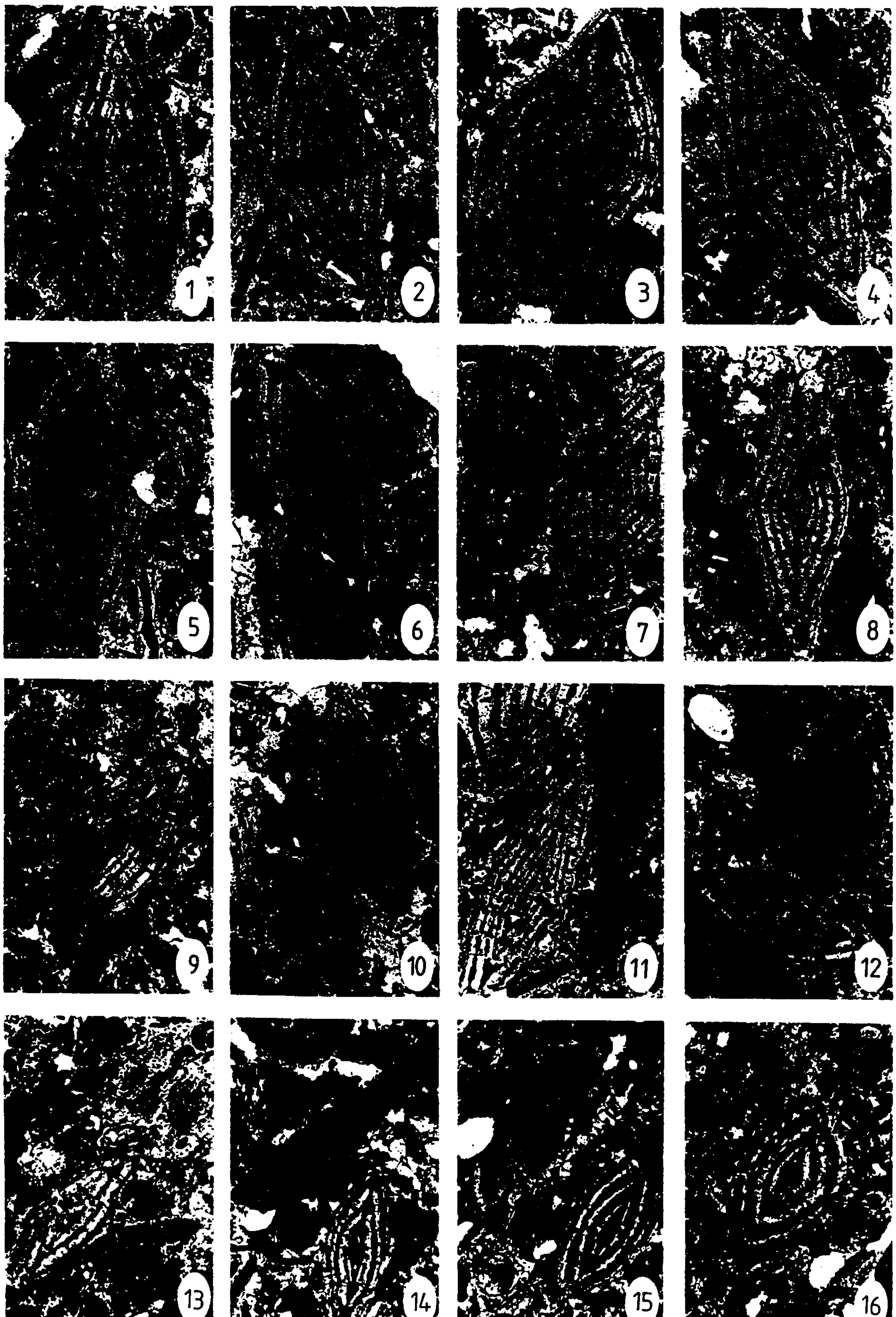


PLATE 13

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing the peloidal, skeletal packstone - wackestone nature of the microfacies (e.g 1,3,4). These include *Praerhapydionina sp.* (2), *Fusarchaias spp.* (3,10), *Spirolina sp.* (14), *Peneroplis sp.* (5,11), *Guttulina sp.* (9,10), *Rotalia sp.* (8,9), *Turborotalia centralis* (Cuchman & Bermudez, 1937) (5,6,7,8,12 and 15), All P.P. light, X35 except 2,10 C.N.

PLATE 13

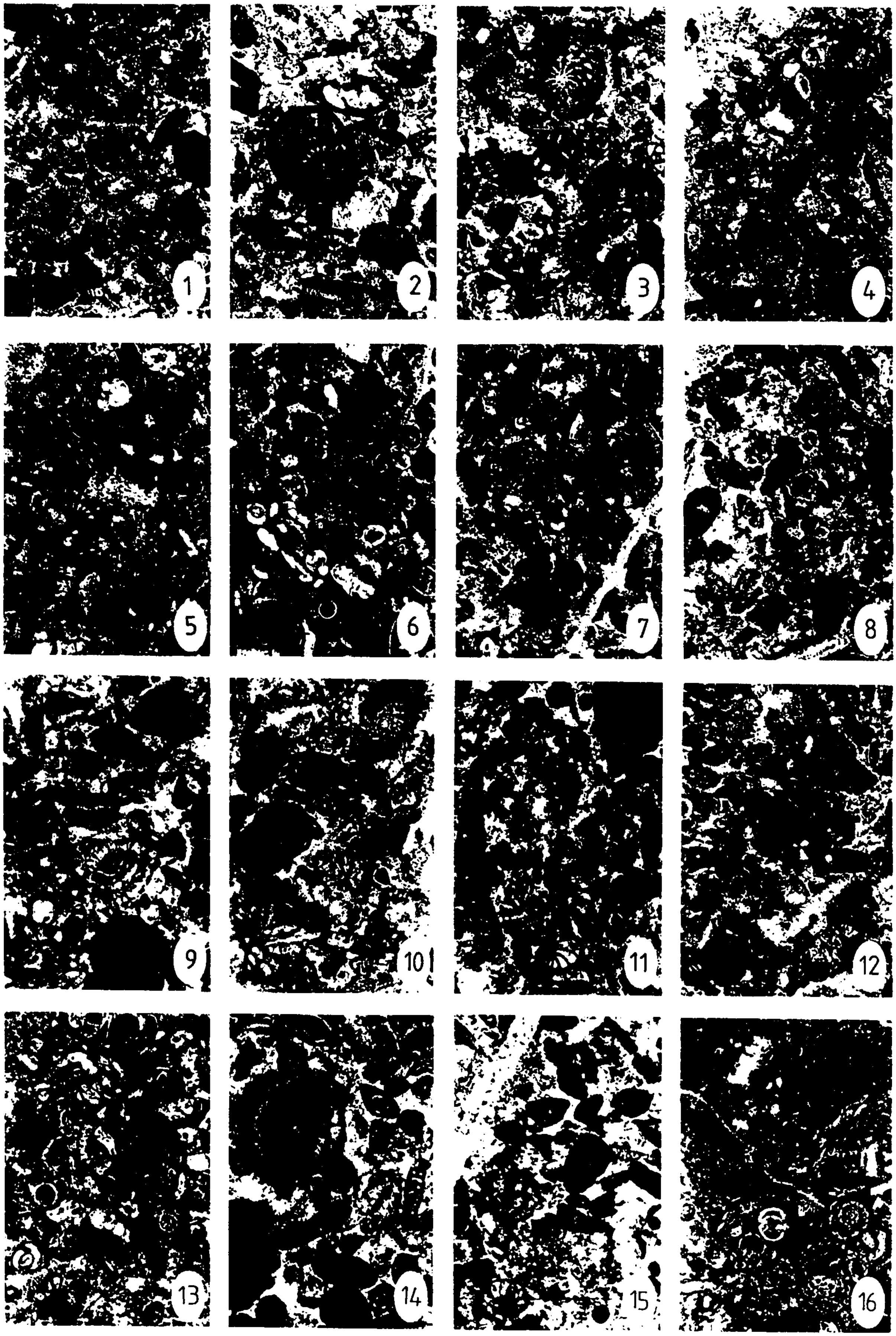


PLATE 14

The Dammam Formation

Microfacies I (cont.)

Figs.1-16: Photomicrographs showing random sections in *Nummulites bouillei* De La Harpe, 1879, form B, (1), *Nummulites retiatus* Raveoda, 1959, form A, (2), *Rotalia sp.* (2,3,10), *Fusarchaias sp.* (14,15), *Peneroplis sp.* (16) *Guttulina spp.* (7,11,12-15), *Turborotalia centralis* (Cuchman & Bermudez, 1937) (4,5,8),

an intraclast (4), All are embedded in a partially recrystallized micritic matrix, with some sparry calcite veins (9). All are P.P. light X35 except 1,5,9,10,13, C.N. and 16 C.N., X140.

PLATE 14

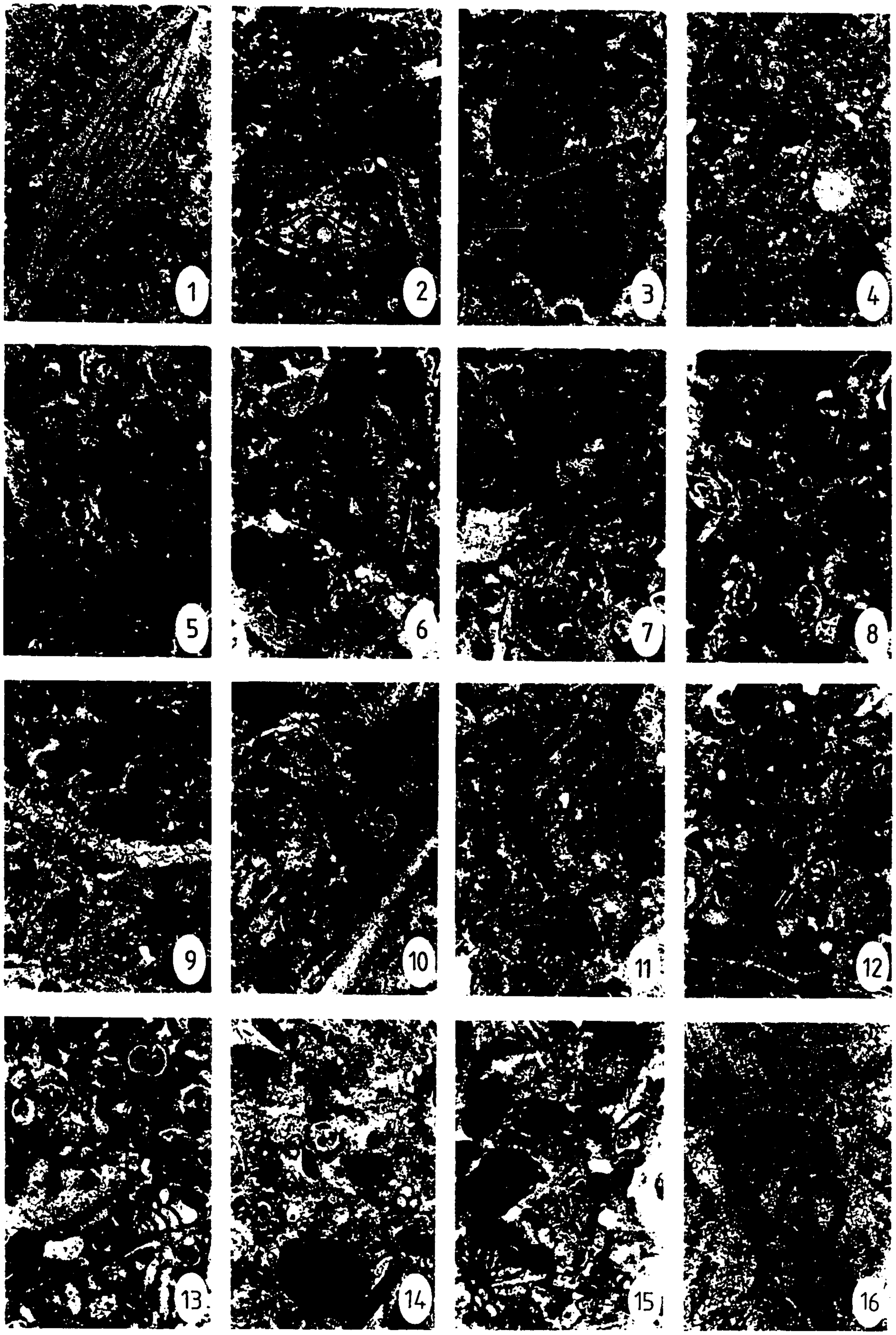


PLATE 15

The Asmari Formation

The Glauconitic, Dolomitic, Skeletal, Sandy, Wackestone Microfacies; Microfacies II.

Figs.1-16: Photomicrographs showing random sections in Nummulitic Foraminiferid remains embedded in a glauconitic, highly iron stained, sandy, dolomitic marly matrix, including *Nummulites bouillei* De La Harpe, 1879, (6), *Nummulites orbignyi* (Galeotti), 1837, (7,8), *Nummulites budensis* Hantken, 1875, (4,9,10,11), *Nummulites intermedius* D'Archiac, 1846, form B, (11-13), *Nummulites vascus* Joly & Leymerie, 1848, (14-16), *Operculina sp.*, (5), *Textularia sp.*, (1,2) P.P. light, X35 except 2 C.N., X35.

PLATE 15

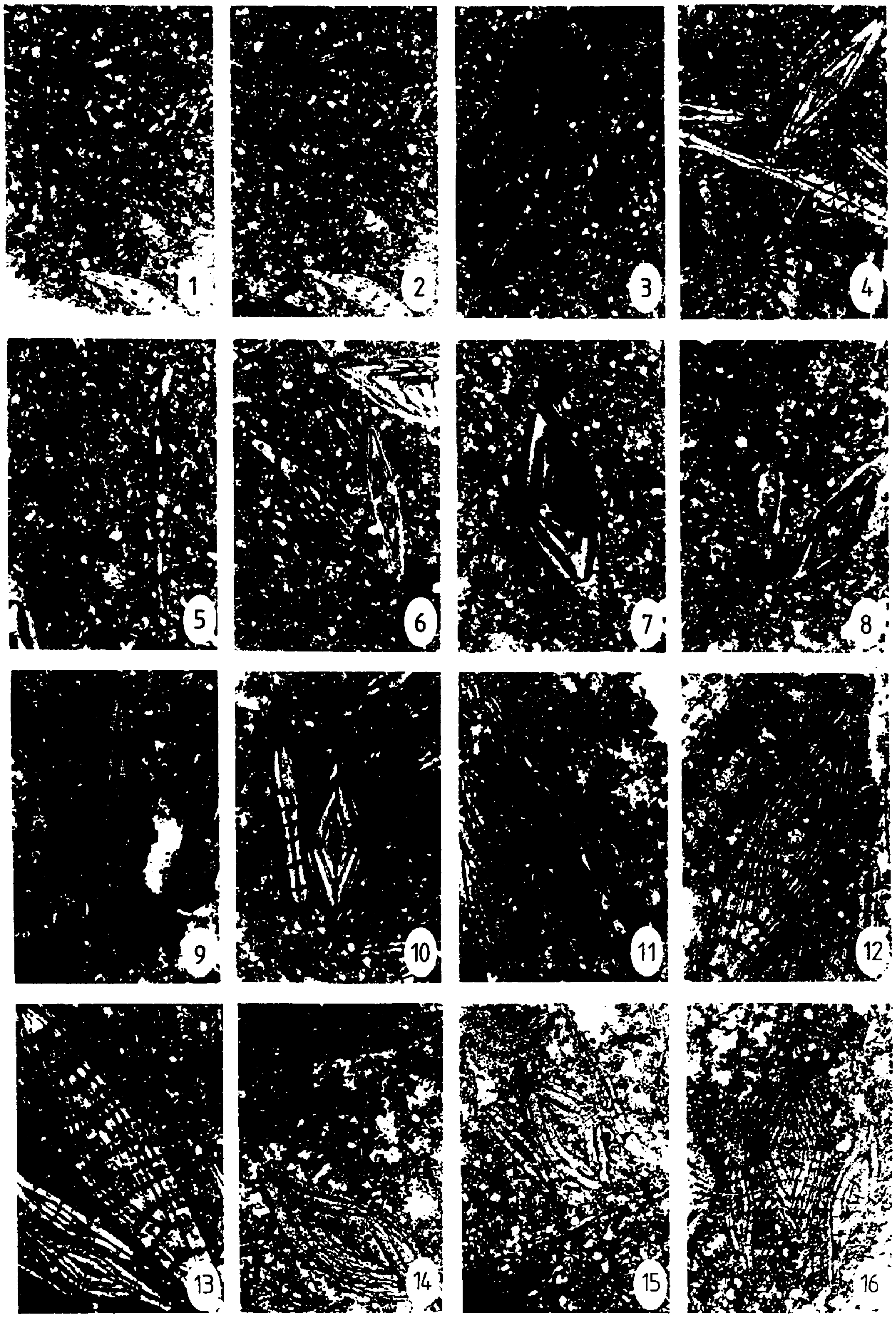


PLATE 16

The Asmari Formation

The Algal Floatstone Microfacies, Microfacies III:

Figs.1-16 : Photomicrographs showing the mottled nature of the microcrystalline calcite of the matrix with some recrystallized batches, disseminated skeletal fragments and algal remains including *Discocyclina sp.* (14), *Victoriella sp.* (15) echinodermal plate (16), recrystallization batches of sparry calcite, probably indicating subaerial exposure (8,12,13). All P.P. light, X35 except 16 C.N.

PLATE 16

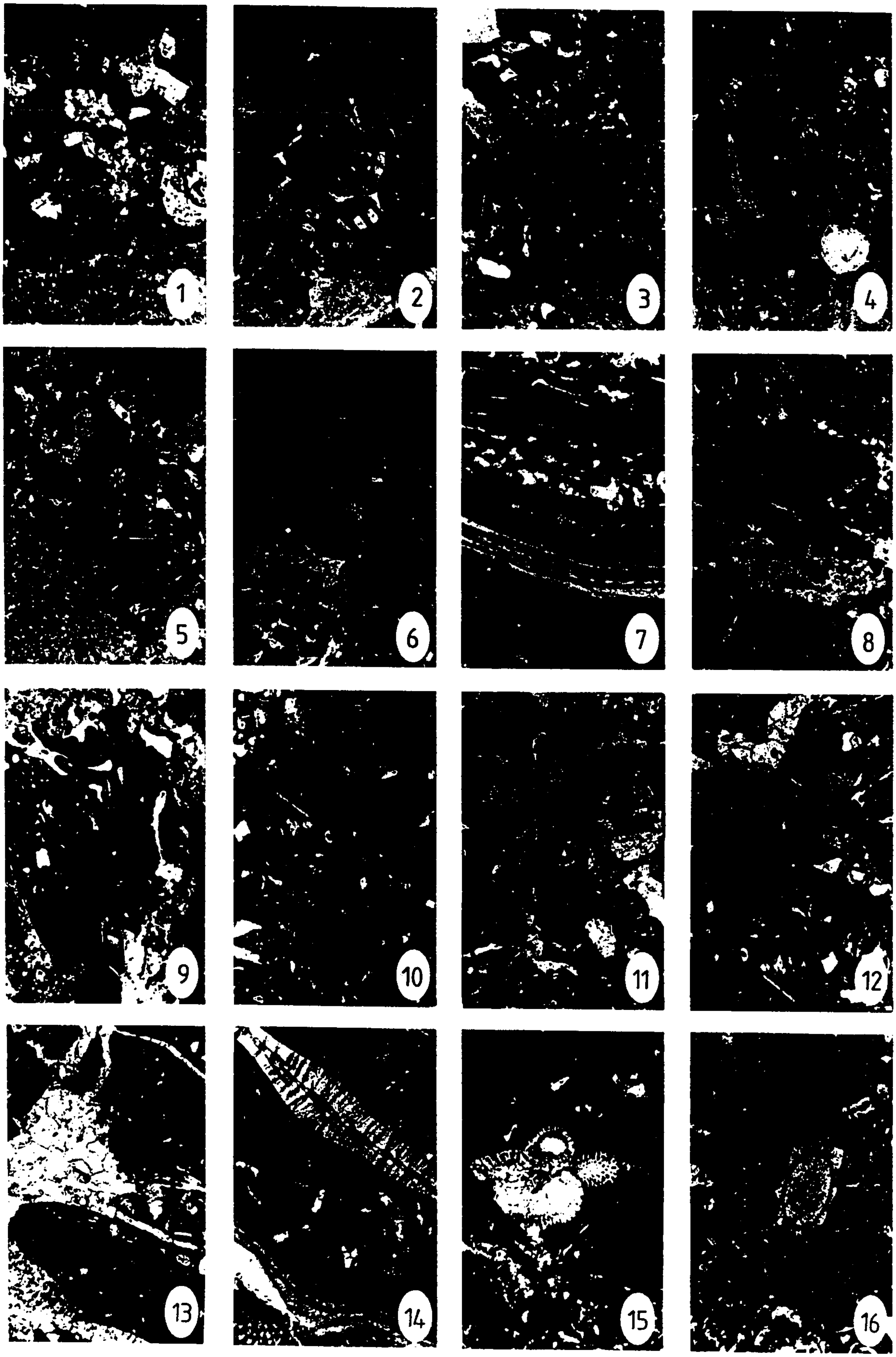


PLATE 17

The Asmari Formation

Microfacies III..(cont.)

Figs.1-16: Photomicrographs showing the algal oncoids where the solid nuclei are surrounded by *Lithothamnium* coating (figs.1-8), with geopetal structures (figs.2,3,4) and some skeletal fragments(9-16), embedded in a micritic matrix P.P. light, X 35, except 9,12,13,14 C.N.

PLATE 17

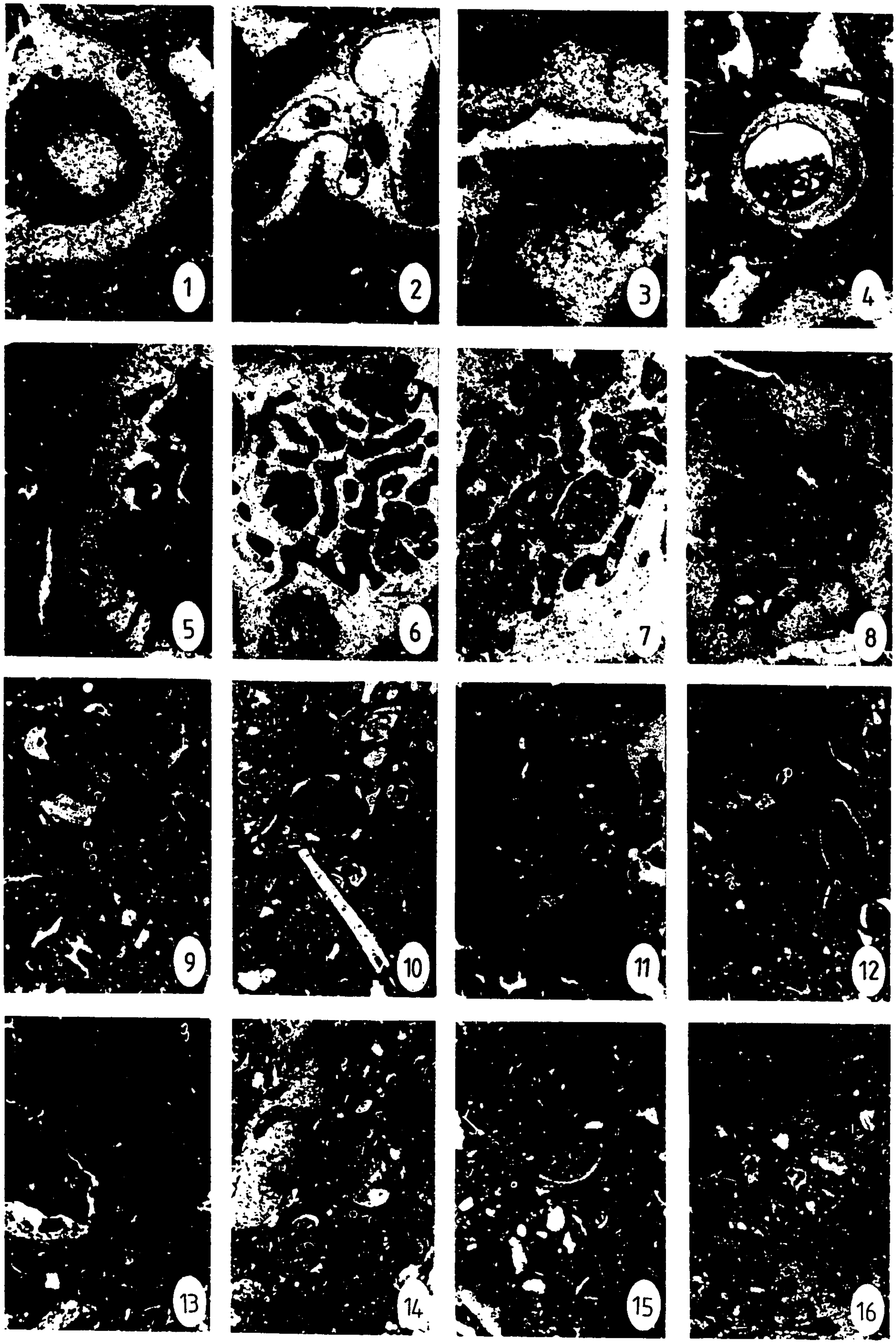


Plate 18

The Asmari Formation

Microfacies III..(cont.)

Figs.1-16: Photomicrographs showing random section in Skeletal grains including *Subterraniphyllum thomasi* (fig.2), *Borelis sp.* (fig.6), *Turborotalia centralis* (Cuchman & Bermudez, 1937) (fig.12) *Victoriella sp.* (figs.11,15), Milolids (fig.3), and *Rotalia sp.* (figs.13,14). All P.P. light; X35 except 9,10,11 C.N. and 14,15,16 C.N.,X140.

PLATE 18

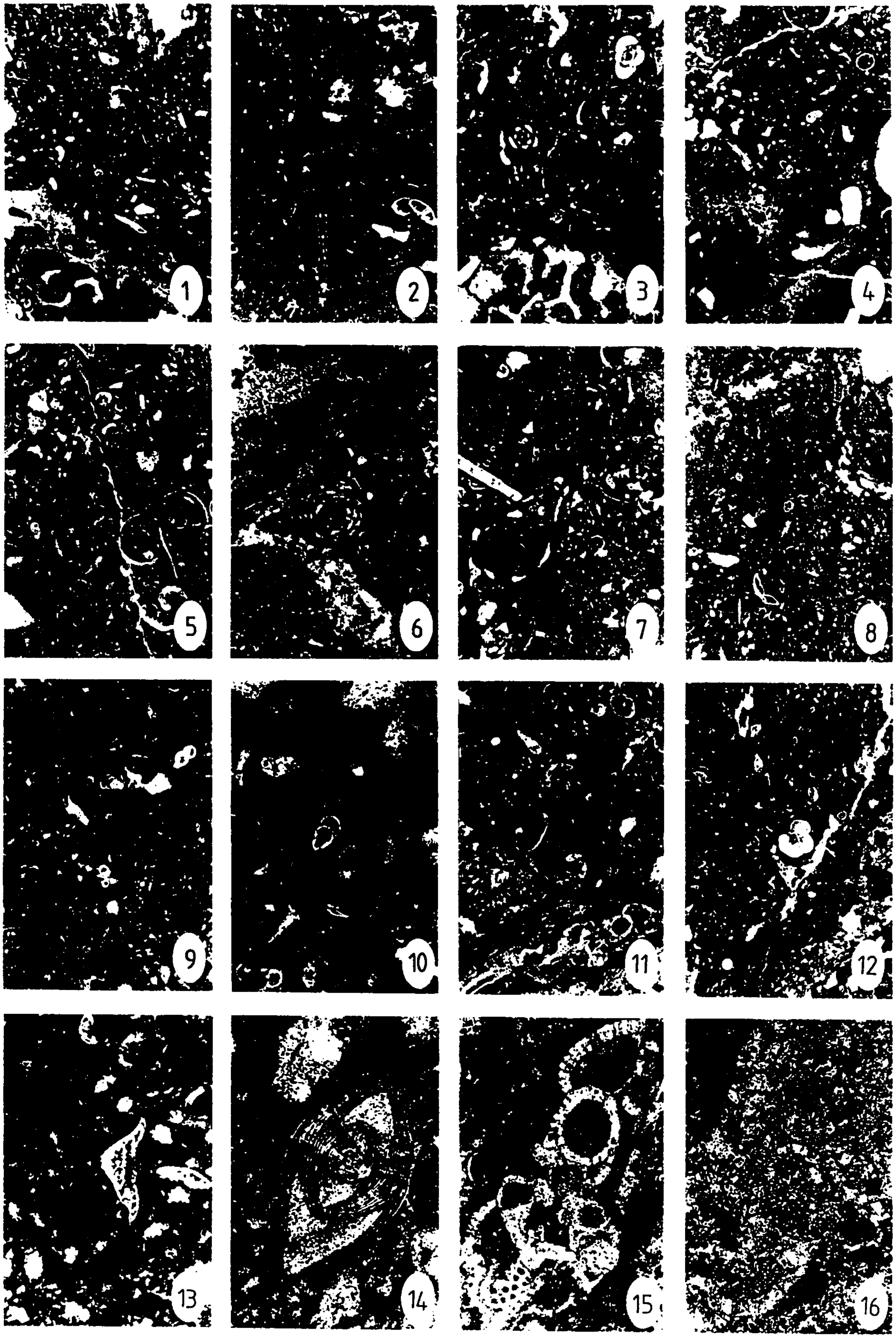


PLATE 19

The Asmari Formation

The Reefal Boundstone Microfacies; Microfacies IV:

Figs.1-16: Photomicrographs showing typical boundstone (baffelstone) (figs.1-6), with some sparrycalcite recrystallization (figs.7,16), borings (figs.5,6), geopetal structure (fig.8) and some foraminiferid remains including *Operculina sp.* (*fig.10*), *Heterostegina sp.* (*figs.9,11,12*), *Borelis sp.and an Ostracoda shell* (*figs.13,14*) P.P. light, X 35 except 1,6,9,14 C.N.

PLATE 19

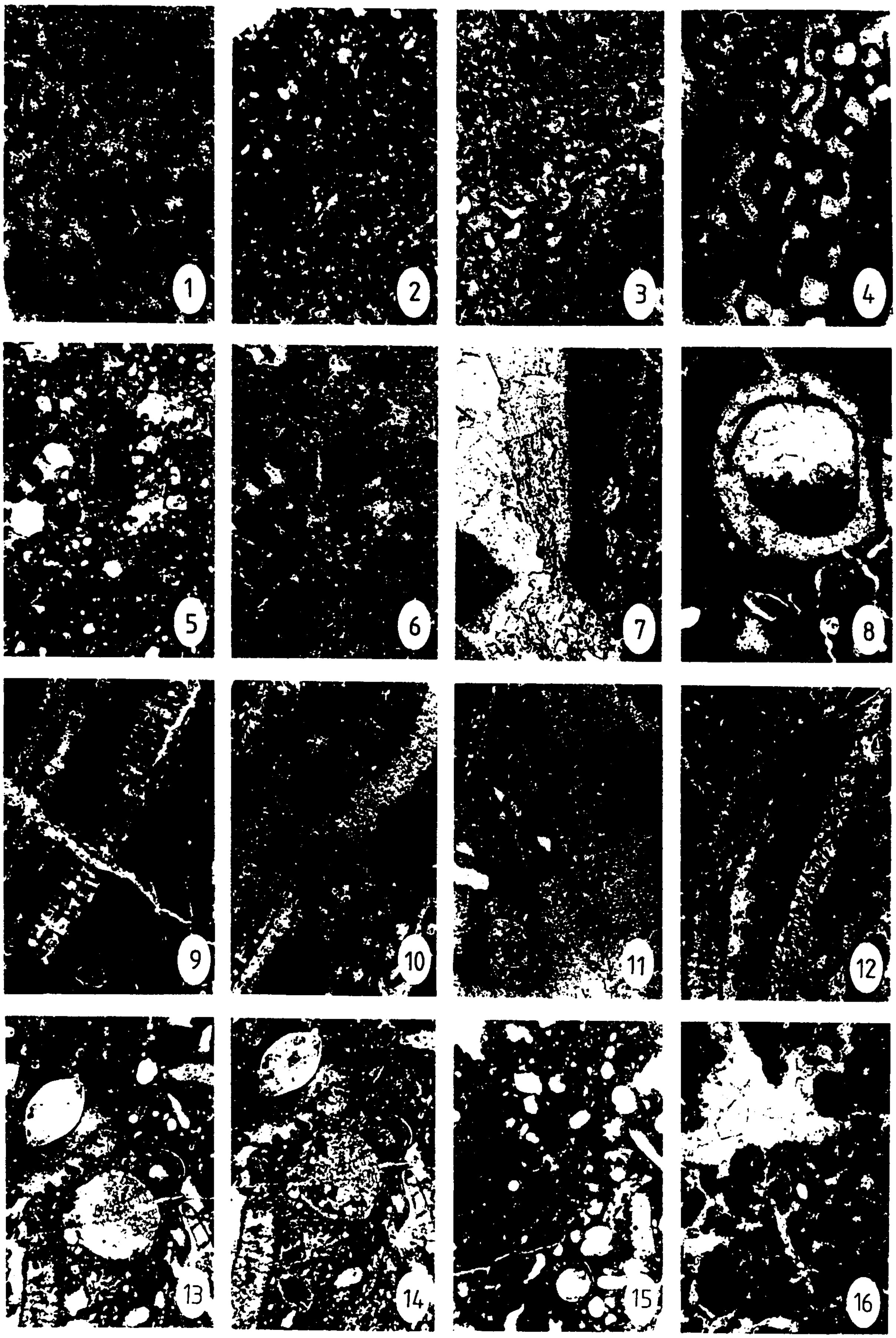


PLATE 20

The Asmari Formation

The Dolomitized, Peloidal, Nummulitic Packstone Microfacies, Microfacies V:

Figs.1-16: Photomicrographs showing the calcarenitic nature of this microfacies in which the skeletal grains are represented by Foraminiferid remains and debris of the skeletal fragments that are packed within a micritic matrix. These Foraminiferid remains include *Heterostegina spp.* (figs.5,6,7), *Archaeolithothamnium sp.* (fig.8), *Operculina complanata* Defrance, 1822, (figs.9,10), *Nummulites vascus* Joly & Leymeric, 1848, (figs.13-16), echinodermal spine (fig.12). They also show some secondary dolomite rhombs scattered in the matrix. (fig.11). P.P. light, X 35 except 8 X140.

PLATE 20

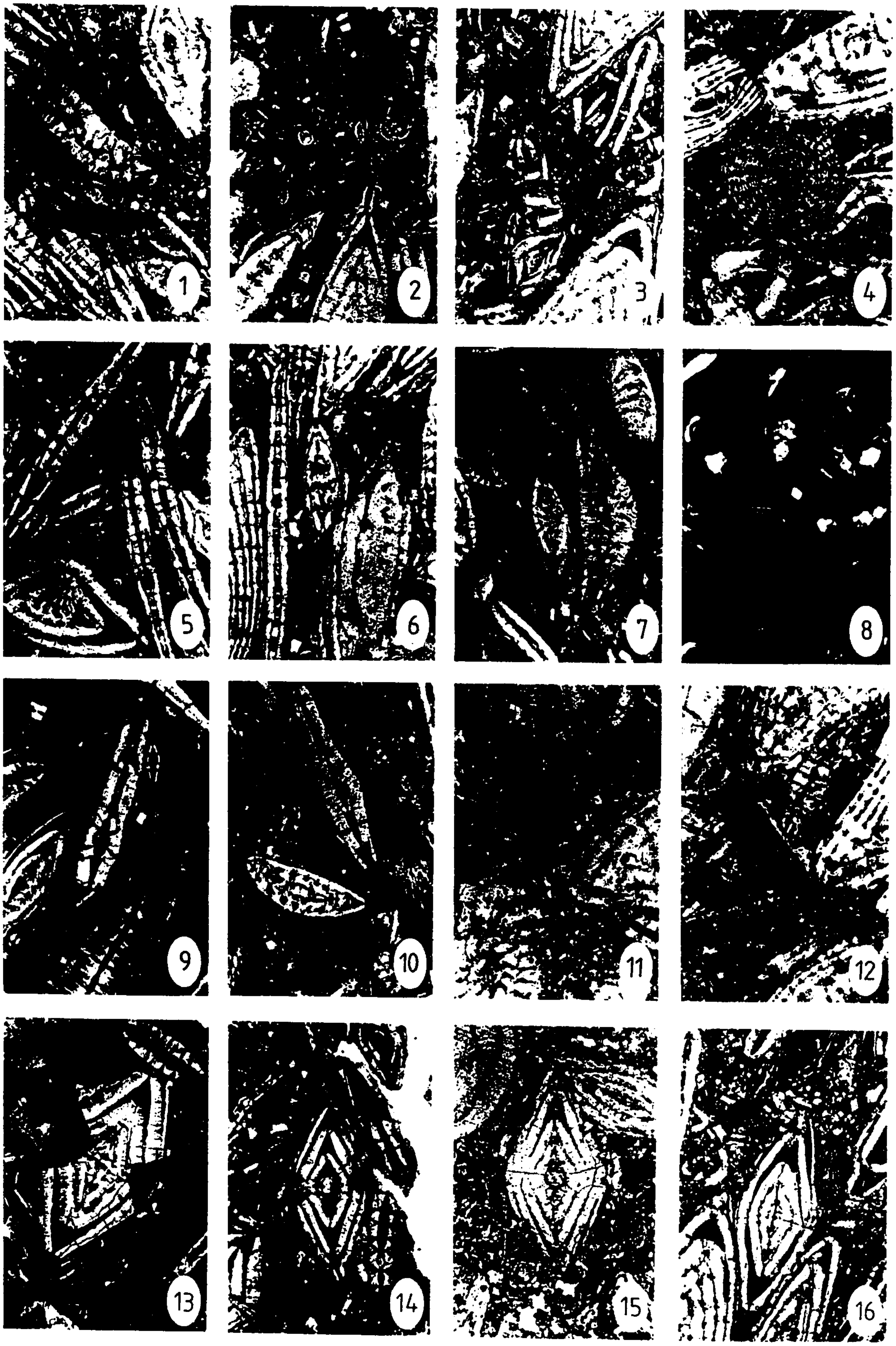


PLATE 21

The Asmari Formation

Microfacies V; ...(cont.)

Figs.1-16: Photomicrographs showing axial sections in *Nummulites intermedius* D'Archiac, 1846, form B, (figs.1-8), form A, (figs.9-13) packed in a micritic matrix. They also showing *Heterostegina sp.* (fig.14), *Nummulites vascus* Joly & Leymerie, 1848, (fig.15), *Operculina sp.* (fig.15), echinodermal spine (fig.14), and a close up of a large solitary corals with sparry fillings of the chambers (fig.16). P.P. light, X35 except 11,12,15 C.N. and 16 C.N., X140.

PLATE 21

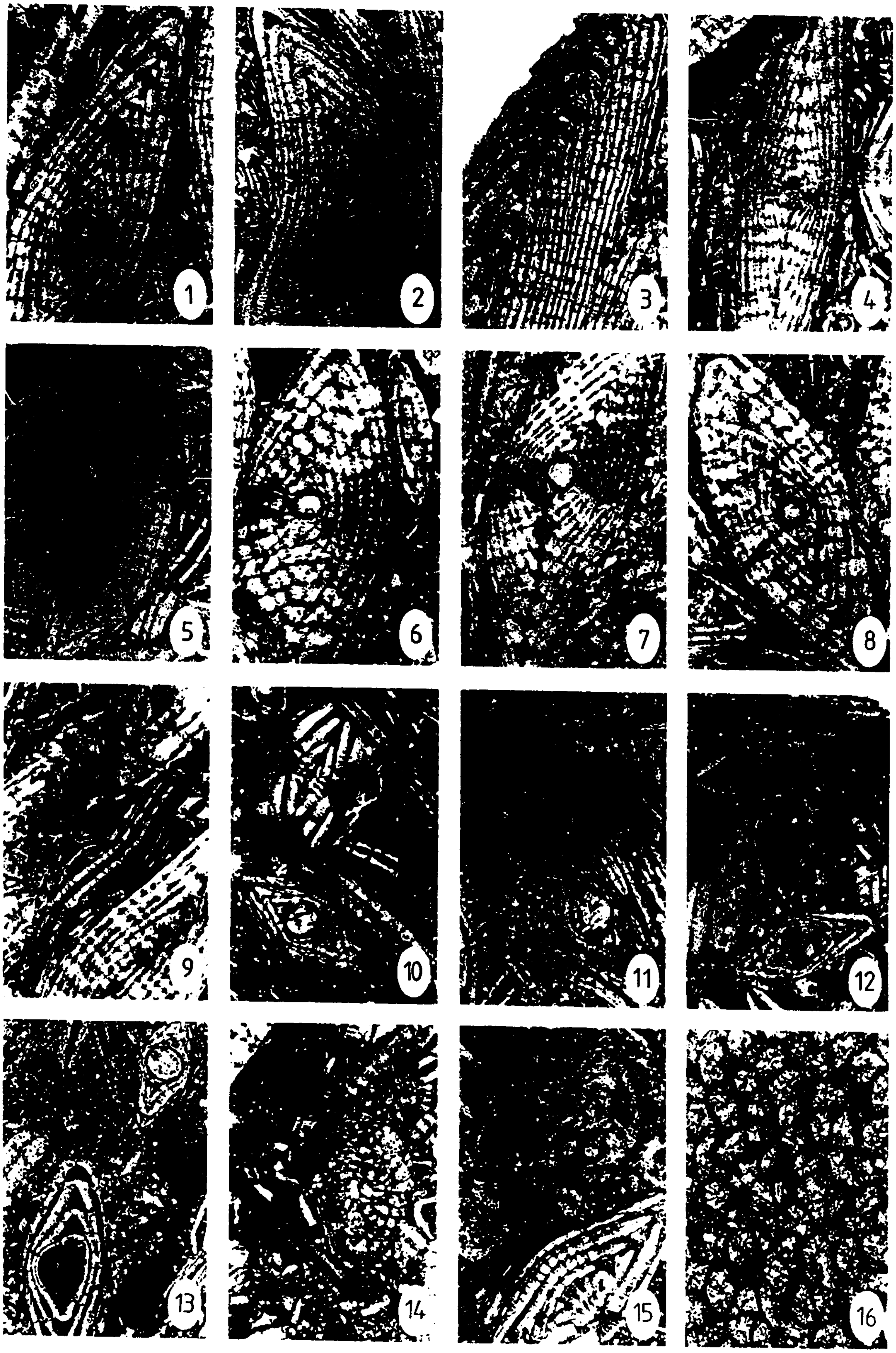


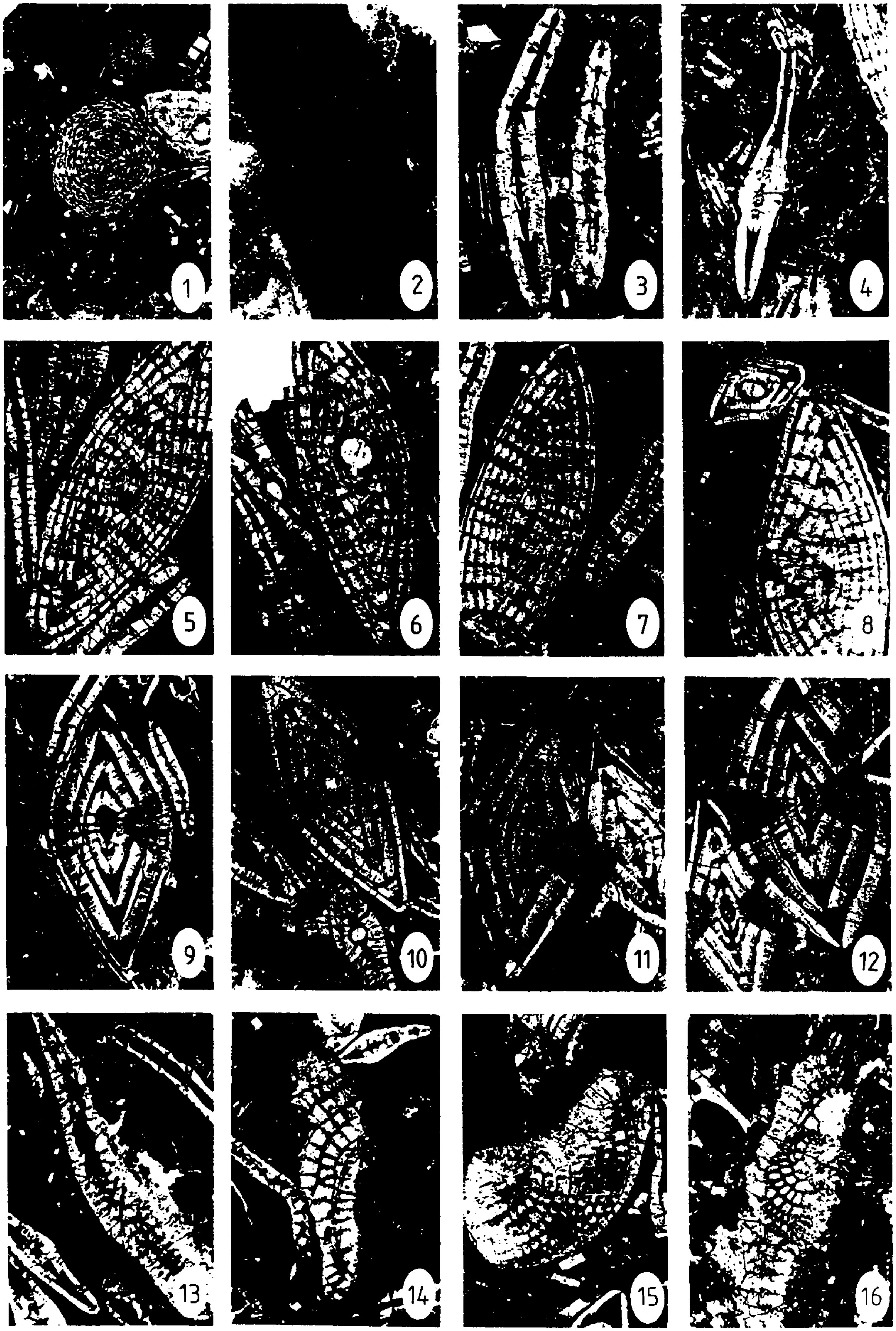
PLATE 22

The Asmari Formation

Microfacies V; ...(cont.)

Figs.1-16: Photomicrographs showing random sections in Foraminiferid remains packed in a partially recrystallized and dolomitized matrix, including an equatorial section in *Borelis sp.* (1), a random section in *Lithophyllum sp.* (2), axial sections in *Operculina complanata* (3,4), axial sections in *Nummulites intermedius* (5-8), axial sections in *Nummulites vascus* (9-12), and random sections in *Heterostegina cf. H. papyracea* (13-16). All P.P. light, X35 except 11,12 C.N.

PLATE 22



APPENDIX

THE PALEOGENE ROCKS IN ARABIA

Main Paleogene Rock Units In Arabia

1. Early Paleogene Rocks In Saudi Arabia:

1.1. The Umm Al Radhuma Formation:-

Authors : Henry and Brown, 1935 (unpublished report; see Steinecke and others, 1958 ; Powers and others, 1966; Powers, 1968).

Type Section: Umm Radhma water wells (*Lat.*28°41′*N.*,*Long.*44°41′*E.*).

Reference Section: the steep walls of wadi Al-Batin, along a 70 km-long traverse from the top of the Linah Escarpment northeast along W. Al-Batin.

Thickness : 243 m at the Reference Section.

Lithofacies: Light colored, foraminiferal micritic and calcarenitic limestones, dolomitic limestones, and dolomites. Towards the east, in the Rub′ Al Khali basin, subsurface samples of the formation show some shaly intercalations near the base (Hasson, 1985).

Boundaries: The lower boundary is marked by an unconformity which separates the Umm Al-Radhuma Formation from the underlying Aruma Group, involving parts of the Latest Cretaceous and most of the Paleocene, while the upper boundary is conformable with the overlying Rus Formation.

Age : Paleocene to Early Eocene age, but the Paleocene succession is truncated from the base by the Cretaceous - Paleogene unconformity and hence is not complete.

1.2. The Rus (Umm Al-Ru'aus) Formation:

Authors : R. A. Bramkamp, 1946 (unpublished report; see Steincke and others, 1958 ; Powers and others, 1966; Powers, 1968).

Type Section: Umm Al-Ru'aus hill, Dhahran; Saudi Arabia, (*Lat.*26°19'04"*N.*, *Long.*50°07'51"*E.*)).

Thickness : 56 m. at the Type Section.

Lithofacies: -A basal, gray, compact, dolomitic limestone unit with minor chalk and quartz geodes.

-A middle, marl and limestone unit with some gypsum and quartz geodes.

-An upper, chalky limestone unit becoming more calcarenitic towards the top.

Boundaries: Both the upper and lower boundaries are conformable with the overlying Dammam and the underlying Umm Al-Radhuma Formations, respectively.

Age : According to its stratigraphic position, the Rus Formation was considered to be of Early Eocene (Ypresian) age (*cf.* Steincke and others, 1958; Powers and others, 1966; Powers, 1968), however, both Hasson (1985) and Al-Tamimi (1985) considered the Rus Formation to be of Early Lutetian age.

1.3. The Dammam Formation:

Authors : R.A. Bramkamp, 1941 (unpublished report; see Steineke and others, 1958 ; Powers and others, 1966; Powers, 1968).

Type Section: Dammam Dome, Dhahran, Saudi Arabia, *Lat.*26°19′16″*N.*, *Long.*50°04′50″*E.*

Thickness : 32.5 m. at the Type Section.

Lithofacies: The Dammam Formation is divisible into five members from base to top as follows:

- The Midra Shale Member: Yellow to brown, fissile shale.
- The Saila Shale Member: Dark to brown-yellow, clayey shale and gray-buff limestones.
- The *Alveolina* Limestone Member: Light tan, partially recrystallized limestone.
- The Khobar Limestone Member: brownish, partially recrystallized, marly, nummulitic limestone.
- The Alat Limestone Member: Cream to Tan colored, chalky, porous, dolomitic marl.

Boundaries: The lower boundary with the underlying Rus Formation is conformable, while the upper boundary is truncated by the post-Dammam unconformity which is one of the major unconformities in the Phanerozoic succession of Arabia and spans the Late Eocene-Oligocene time.

Age : Originally considered to be of Early-Middle Eocene age (e.g Powers and others, 1966; Powers, 1968), but it is now limited to the Middle Eocene (Lutetian) age by Al-Tamimi (1985).

2. Early Paleogene Rocks In Southwestern Iraq:

2.1.The Umm Al Radhuma Formation:

Authors : Owen and Nasr (1958).

Reference Section: Zubair No.3 well, and outcrops in the western Iraqi desert.

Thickness : 1500 ft. (459 m) in the Reference Section.

Lithofacies: Anhydritic, dolomitic, and marly dull whitish to buff limestone with some chert in its upper parts.

Boundaries: While Owen & Nasr (1958) described the lower contact of the Umm Al-Radhuma Formation with the underlying, Late Cretaceous Tayarat Formation as conformable, Al-Naqib (1967) stated that in the outcrop section, there is a distinct unconformity between the two formations. Contrary to this, both authors (*op.cit.*) agreed that the upper contact with the overlying Rus Formation is conformable.

Age : Paleocene to Early Eocene (cf. Owen & Nasr, 1958; Al-Naqib, 1967).

2.2.The Rus Formation

Authors : Owen and Nasr (1958).

Reference Section: Zubair No.3 well.

Thickness : 307 ft. (94 m) in the Reference Section.

Lithofacies: Massive, white, crystalline anhydrite with intercalations of unfossiliferous limestone and thin blue shale and marl interbed.

Boundaries: Contact with the overlying Dammam Formation is generally conformable, but with local unconformities (cf. Owen & Nasr,1958), or unconformable with local conformity (cf. Van Bellen and others, 1959; Al-Naqib, 1967).

Age : Middle Eocene (Owen & Nasr, 1958), or Early-Middle Eocene (Van Bellen and others, 1959).

2.3.The Dammam Formation:

Authors : Owen and Nasr (1958).

Reference Section: Zubair No.3 well (also crops out in western Iraq).

Thickness : 738 ft. (225 m) at the Reference Section.

Lithofacies: Cream to gray, recrystallized nummulitic limestone locally leached out and very porous, with some blue, silty, waxy shale streaks near the base. Towards the top, it becomes dark-gray to black, pyritized and dolomitized.

Boundaries: Lower boundary conformable, while upper boundary is truncated by a major unconformity that separates it from the overlying Ghar Formation of Miocene age (*cf.* Al-Naqib, 1967).

Age : Middle Eocene (*cf.* Owen & Nasr, 1958; Al-Naqib, 1967).

3.The Early Paleogene Succession in Kuwait:

3.1.The Umm Al Radhuma Formation:-

Authors : As in Saudi Arabia.

Reference Section: In the Burgan No.10

Thickness : 1610 ft. (493 m) at the Reference Section.

Lithofacies: Limestone and dolomitic limestone intercalating with microcrystalline dolomite and anhydrite,as well as, some partings of black calcareous shale are found in the lower part.

Boundaries: The lower boundary with the underlying Cretaceous Formation is representing a hiatus with debatable duration, while the upper boundary with the overlying Rus Formation is conformable

Age : It was assigned to Paleocene - Early Eocene by Owen & Nasr, 1958, however, El-Nakhal & El-Naggar, 1989, revised the age to be of Late Paleocene-Early Eocene.

3.2.The Rus Formation:

Authors : As in Saudi Arabia.

Reference Section: In the Burgan No.10

Thickness : 250 ft. (76 m) at the Reference Section.

Lithofacies: White to gray, dense anhydrite with grayish white chalky limestone and minor dolomite interbeds, as well as traces of shales and marls.

Boundaries: Both the upper and lower contacts are conformable.

Age : Middle Eocene (base of Lutetian) age,(*cf.* Owen & Nasr, 1958; Al-Tamimi, 1985; Hasson, 1985).

3.3.The Dammam Formation:

Authors : As in Saudi Arabia.

Reference Section: In the Burgan No.10

Thickness : 583 ft. (178 m) at the Reference Section.

Lithofacies: The basal part is mainly white to gray, soft, chalky, dolomitic limestone interbeded with greenish gray, nummulitic marl. These are followed by cream, dense, nummulitic limestone grading upward into intercalated dolomites and anhydrites, which suggest a tidal flat environment at the top of The Dammam Formation representing a typical shallowing upward sequence.

Boundaries: The upper boundary is unconformably overlain by the Ghar Formation, while the lower one is conformable.

Age : It was considered by many Authors to be of Early to Middle Eocene age (e.g Owen & Nasr, 1958; El-Nakhal, 1973, 1988). However, El-Nakhal & El-Naggar (1989) have mentioned that the age of the Dammam Formation may be extended to the Late Eocene (Late Lutetian - Early Priabonian).

4. Early Paleogene Rocks In Qatar:

4.1.The Umm Al Radhuma Formation:

Authors : As in Saudi Arabia.

Reference Section: Q.P.C. well Dukhan No.22, Qatar (*Lat.*26°19′04″ *N*, *Long.*50°07′51″ *E*).

Thickness : 1077 ft. (328 m) at the Reference Section.

Lithofacies: Light brown to light gray, partially dolomitic, porous, silicified limestone at the top, becoming more argillaceous near the bottom, to entirely blue-gray marls at the base.

Boundaries: The lower contact with the underlying Late Cretaceous Simsima Formation is regionally disconformable, while the upper contact with the overlying Rus Formation is conformable (*cf.* Sugden, 1975).

Age : Paleocene to Early Eocene (Smout, 1954).

4.2.The Rus Formation:

Authors : As in Saudi Arabia.

Reference Section: At the cliffs of Jabal Dukhan, Qatar, (*Lat.*25°26′*N*,*Long.*50°47′*E*).

Thickness : 120 ft. (36 m) at the Reference Section.

Lithofacies: Dolomitic chalk with occasional calcarenite interbeds and chert nodules.

Boundaries: The contacts are conformable with both the underlying Umm al-Radhuma and the overlying Dammam Formations (*cf.* Sugden, *op.cit.*).

Age : On the basis of its stratigraphic position, it was considered by Sugden (1975) to be of Early Eocene age.

4.3.The Dammam Formation:

Authors : As in Saudi Arabia.

Reference Section: In outcrop from *Lat.*25°26′*N*,*Long.*50°47′*E* to *Lat.*25°28′*N*,*Long.*50°49′*E*, along the cliffs of Jabal Dukhan.

Thickness : 170 ft. (52 m) at the Reference Section.

Lithofacies: Mainly light gray limestones, intercalated with white chalky dolomites, and some shales and marls at the bottom.

Boundaries: The surface of the Dammam Formation is exposed and highly eroded in the area of the reference section.

Age : Middle Eocene (Lutetian).

5. The Early Paleogene Rocks in the U.A.E.:

5.1 The Early Paleogene succession in Abu Dhabi:

5.1.1. The Umm Al Radhuma Formation:

Authors : As in Saudi Arabia.

Reference Section: Belbazem-1 well of ADMA (offshore).

Thickness : 1232 ft. (377 m) at the Reference Section.

Lithofacies: Dolomitic to partially argillaceous limestone with some thin shale intercalations at the base.

Boundaries: The lower boundary was described as gradational and the upper boundary was also described as apparently conformable (ADMA unpublished report, 1985; Al-Sharhan, 1989).

Age : Paleocene to Early Eocene .

5.1.2.The Rus (Umm Al-Ru'aus) Formation:

Authors : As in Saudi Arabia.

Reference Section: ADMA Zakum-45 well (offshore).

Thickness : 330 ft. (101 m) at the Reference Section.

Lithofacies: Extensive evaporitic succession composed mainly of alternating bedded anhydrite and dolomite with some argillaceous limestone at the base.

Boundaries: Both boundaries are conformable.

Age : Early Eocene.

5.1.3.The Dammam Formation:

Authors : As in Saudi Arabia.

Reference Section: ADMA Belbazem-1 well

Thickness : 769 ft. (235 m) at the Reference Section.

Lithofacies: Marly to argillaceous limestone changing upwardly into shallower, nummulitic, open shelf to platform margin packstone - grainstone, then ending with tidal flat dolomite.

Boundaries: The contact with the overlying Asmari Limestone is unconformable onshore of Abu Dhabi (Pininngton, 1981; Al Sharhan, 1989), becoming gradually conformable offshore (ADMA unpublished report).

Age : Middle Eocene in the west, to Middle - Late Eocene in the East.

5.2. The Early Paleogene succession in Dubai:

5.2.1. The Pabdeh Formation:

Authors : R.K.Richardson, 1924; Kent, Slinger, and Thomas, 1951

Type Section: At the Tang-e Pabdeh type section on the southeastern end of Kuh-e Pabdeh, Iran.

Reference Section in Dubai: No available data.

Thickness : In the Type Section, 2620 ft. (801 m) , (James & Wynd, 1965), but much reduced in Dubai to the range of 1000 ft (306 m), (Pininngton, 1981).

Lithofacies: Argillaceous limestones with glauconite and marl at the base.

Boundaries: The upper boundary is conformable with the overlying Dammam Formation, but the lower one represents a considerable hiatus.

Age : Paleocene to Early Eocene

5.2.2. The Dammam Formation:

Authors : As in Saudi Arabia.

Reference Section: No available data.

Thickness : No available data, but in the range of 1600 ft (489 m), (Pininngton, 1981).

Lithofacies: Dolomitic limestone with anhydritic streaks at the base. In the more basinal areas, the formation becomes marly and shaly.

Boundaries: both of the upper and lower boundaries are conformable.

Age : Middle-Late Eocene (Pininngton, 1981).

6. The Early Paleogene succession in Interior Oman (Dhofar):

6.1. The Hadhramout Group:

Authors : R. Wetzel and D.M. Morton, 1948 (unpublished report; see Clarck, 1988).

Type Area: Dhofar.

Description: Although slightly more complete, the Hadhramout Group is stratigraphically equivalent to the Hasa Group of Saudi Arabia and embraces the same formations of Umm Al Radhumah, Rus and Dammam, plus the Andhur Formation. The usage of the term Hadhramout instead of Hasa was suggested by its authors to reflect the wider lithological variation in Interior Oman.

Age : Paleocene - Middle Eocene, to possibly Late Eocene (in the Dammam Formation of the northern area of Interior Oman).

6.1.1.The Umm Al Radhumah Formation:

Authors : As in Saudi Arabia.

Reference Section: In P.D.O. Beladi-1 well, Oman, (*Lat*.22°20′24″ *N*, *Long*.55°45′47″ *E*).

Thickness: 1119 ft. (341 m) at the Reference Section.

Lithofacies: Slightly to highly dolomitic limestone with minor argillaceous horizons and a major shale/marl unit forming the base and known as the Shammar Member.

Boundaries: The lower boundary represents a hiatus, between the underlying Late Cretaceous rocks and the base of the Umm Al Radhuma Formation, while The Upper one is conformable with the overlying Rus Formation.

Age : Late Paleocene - Early Eocene.

6.1.2.The Rus (Umm Al Ru'aus) Formation:

Authors : As in Saudi Arabia.

Reference Section: In P.D.O. Beladi-1 well, Interior Oman, (*Lat*.22°20′24″*N*,*Long*.55°45′47″*E*).

Thickness : 426 ft. (130 m) at the Reference Section.

Lithofacies: Evaporite, gypsum or anhydrite with some dolomite and dolomitic marl.

Boundaries: Both of the boundaries are conformable.

Age : Early Eocene (based on the stratigraphic position).

6.1.3.The Dammam Formation:

Authors : As in Saudi Arabia.

Reference Section: In P.D.O. Beladi-1 well (*Lat.*22°20′24″*N*,*Long*.55°45′47″*E*).

Thickness: 464 ft. (142 m) at The Reference Section .

Lithofacies: Slightly dolomitized limestone with minor marly interbeds.

Boundaries: The lower boundary is conformable while the upper one is truncated by the post-Dammam unconformity.

Age : Middle Eocene, with possible extension to Late Eocene in the extreme northern part of Interior Oman.

6.1.4.The Andhur Formation:

Authors : R. Wetzel and D.M. Morton, 1948 (unpublished report; see Clarck, 1988).

Type Section: Wadi Andhur, Dhofar plateau. (*Lat*.25°26′*N*,*Long*.50°47′*E*).

Thickness: 141 ft. (43 m) at The Type Section.

Lithofacies: Argillaceous limestone and dolomite with marly and shaly interbeds.

Boundaries: The lower boundary is conformable, while the upper one is disconformable.

Age : Middle Eocene.

Correlation: The Andhur Formation is the more argillaceous lateral equivalent of the uppermost members of the Dammam clean limestone.

7.The Early Paleogene rocks in the southern Yemen:

7.1.The Umm Al Radhuma Formation:

Authors : As in Saudi Arabia.

Reference Section: At Say'un in Wadi Hadhramout.

Thickness: 58 m at the Reference Section.

Lithofacies: Basal dolomite, followed upwardly by fissile shale and nodular limestone, becoming marly further upward and extensively weathered at the top.

Boundaries: The lower boundary is disconformable, while the upper one is conformable.

Age : Paleocene

7.2.The Jeza' Formation:

Author : Beydoun, 1960.

Type Section: In the Masilah basin in western Al Maharah, Hadhramout, Southern yemen.

Thickness: 133 m.

Lithofacies: Alternation of fissile shales, marls, limestones and some gypsum bands.

Boundaries: Both of the lower and the upper boundaries are conformable.

Age : Early Eocene.

Correlation: It can be correlated with the upper part of the Umm Al Radhuma Formation in nearby countries, (*cf.* Beydoun ,1988).

7.3.The Rus (Umm Al Ru'aus) Formation:

Authors : As in Saudi Arabia.

Reference Section: Wadi Hibun, Hadhramout, Southern Yemen.

Thickness: 138 m at The Reference Section.

Lithofacies: Gypsiferous to chalky limestones, interbedded with massive gypsum.

Boundaries: Both of the boundaries are described as transitional.

Age : Early Eocene (based on the stratigraphic position).

7.4.The Habshiya Formation:

Authors : R. Wetzel and D.M. Morton, (unpublished data, 1948-50; see Beydoun,1967)

Type Section: Wadi al Jiz, Hadhramout, Southern part of the Yemen Republic.

Thickness: 224 m at The Type Section.

Lithofacies: Grey-green, yellow and pink, fissile shale and chalky, gypsiferous dolomitic limestone.

Boundaries: The lower boundary is conformable while the upper one is unconformable and is truncated by a regional hiatus.

Age : Middle Eocene (Lutetian).

8. The Early Paleogene succession in Central and Northern Oman Mountains:

8.1. Omani Paleogene Formations correlatable with equivalent rock units in nearby countries:

8.1.1. The Jafnayn Formation:

Authors : Nolan and others (1990)

Type Section: East of the Jafnayn village, west of Muscat, Oman. (*Lat.*23°32′05″*N*,*Long*.58°13′10″*E*).

Thickness : 126 m at the Type Section.

Lithofacies: Buff-cream, nodular limestone, changing into yellow marl and marly wackestone in the middle and grading upward into grey-beige limestone that ranges in composition from wackestone, to packstone and grainstone towards the top.

Boundaries: The Upper boundary was described to be apparently conformable although

it may represent a non-sequence or disconformity, while the lower boundary is a low angle unconformity.

Age : Late Paleocene to Early Eocene.

Correlation: Because of its relatively deeper facies, the Jafnayn Formation was treated separately from the Umm Al Radhuma Formation, despite their time equivalency. This is simply because of the fact that the two formations are separated by the basinal facies of Pabdeh Formation and hence, are not juxtaposed and do not interdigitate. Again, the fossil content of these two formations are slightly different.

8.1.2.The Rusayl Formation:

Authors : Nolan and others, 1990.

Type Section: Rusayl village, west of Mascut, Oman. (*Lat.23°32′20″N,Long.58°13′20″E*).

Thickness : 470 ft. (144 m) at the type section.

Lithofacies: Basal variegated shales and marls, partially cherty, with occasional thin, chalky bands, followed upwards by chalky limestone, then variegated shale and marl interbeded with sand and shale, near the base and with bioclastic limestone near the top.

Boundaries: The Upper boundary is conformable, while the lower boundary is disconformable.

Age : Early Eocene (Montenat & Blondeau, 1977).

Correlation: The Rusayl Formation was correlated by Nolan and others(1990) with the Rus Formation, despite their marked lithologic composition, fossil content and age. The Rus Formation was recently proved to be of Early-Middle Eocene age (*cf.* Hasson, 1983, 1985;Al Tamimi, 1985), while the Rusayl Formation was restricted to the Early Eocene.

8.1.3.The Seeb Formation:

Authors : Nolan and others (1990).

Type Section: Roadside section along Nizwa-Muscat road, Batinah coast, Oman.

Thickness : 1163 ft. (356 m) at the type section.

Lithofacies: Beige to brown, bioturbated, nodular, well-bedded, foraminiferal (mainly Miliolid, orbitoidal, alveolinid and occasionally nummulitic) calcarenite throughout the section, but with a middle marly limestone horizon and a marked increase in the nummulitic content towards the top.

Boundaries: The lower boundary of the Seeb Formation was described to be conformable while its top was said to be unexposed.

Age : Middle Eocene (*cf.* Montenat & Blondeau, 1977).

Correlation: The Seeb Formation was correlated by Nolan and others (1990) with the Dammam Formation, but was treated as a new local unit, since the two formations are not juxtaposed and do not interdigitate.

8.2. Omani Paleogene Formations uncorrelatable with nearby countries:

8.2.1. The Ruwaydah Formation:

Authors : Nolan and others(1990).

Type Section: Scattered exposures near Jabal Ruwaydah, north of the Batinah coast.

Thickness : 2940 ft. (900 m) at the type section.

Lithofacies: Beige, tabular, well bedded, hard calcarenite with some chert nodules, shale and marl horizons, and occasional limestone conglomerate (ranging in grain size from pebbles to boulders) derived from the nummulitic and alveolinid Seeb limestone. The top of the section is dominated by occasionally exposed chalky limestone, marl and shale with some bioclastic horizons rich in both foraminiferid and echinoid remains.

Boundaries: Neither the top nor the bottom of the Ruwaydah formation were seen. The basal Ruwaydah lies adjacent to the Late

Cretaceous Thaqab Formation, with no apparent Paleocene rocks in between.

Age : Eocene (*cf.* Nolan, 1990).

Correlation: The Ruwaydah Formation differs from the Pabdeh Formation in the age, and also in the presence of conglomeratic horizons in both its lower and middle parts.

8.2.2.The Muthaymimah Formation:

Authors : Nolan an others (1990).

Type section: The hill section on the north western side of Sayh Muthaymimah, southern of Al-Buraymi, west central Oman Mountains, Oman.

Thickness : 980 ft. (300 m) at the type section.

Lithofacies: Shales, marls and argillaceous limestones, followed upwards by thickly bedded limestone conglomerate including clasts of the late Cretaceous Simsima Limestone, reworked rudist and coral fragments and minor ophiolite clasts. This grades upwards into shale and argillaceous calcirudites and marls with minor conglomeratic lenses and is followed by alveolinid limestone bands, conglomerates, argillaceous limestones, shale and marl with lithic sandstone and limestone bands (with occasional nummulitic remains and lenticular conglomerates which include clasts of Hawasina cherts, Semail ophiolite and reworked Paleogene limestones). Above these rocks, thickly bedded to massive limestone conglomerates with reworked clasts of the Seeb Limestone and lesser amounts of both ophiolite and Hawasina chert debris follow. The top of the succession is poorly exposed, but it is mainly composed of thinly bedded marl and argillaceous limestone, with clasts of ophiolite, Hawasina chert and limestone composition.

Boundaries: The lower boundary is unconformable with the underlying Simsima Formation, while the upper boundary is conformable with an overlying un-named Eocene unit.

Age : Roughly estimated on the basis of both stratigraphical position and fossil content as Paleocene to Middle Eocene.

Correlation: Both of the Muthaymimah and the Ruwaydah Formations are lithologically similar, but due to their age differences (Paleocene to Middle? Eocene for the former and only Eocene for the latter) they were treated separately.

9.The Late Paleogene Rocks in Arabia:

9.1.The Late Paleogene Rocks In Saudi Arabia, Southern Iraq, Kuwait and Qatar:-

Despite detailed investigations in Saudi Arabia, Southern Iraq, Kuwait and Qatar, no fossiliferous, marine Late Paleogene (Late Eocene-Oligocene) rocks have -so far- been detected (*cf.* Thralls and Hasson, 1956; Owen and Nasr, 1958; Steineke and others, 1958; Page, 1959; Powers and others, 1966; Al Naqib, 1967; Milton, 1967; Powers, 1968; Tleel, 1973; Sugden, 1975; Murris, 1980; Hancock and others, 1987; Beydoun, 1988 and El-Nakhal and El-Naggar, 1989).

9.2.The Late Paleogene Succession in the U.A.E:

9.2.1.The Late Paleogene Succession in Abu Dhabi:

9.2.1.1.The Asmari Formation:

Authors : Pilgrim, 1908, 1924

Type Section: At Tang-e Gel-e Tursh on the southwestern flank of Kuh-e Asmari anticline, Iran.

Reference Section: ADMA Umm Addalkh-1 well in the east, and ADMA Belbazem-1 well in the west

Thickness : In the type section :- 1030 ft.

In the reference section :- about 200 ft in the west and about 450 ft in the East.

Lithofacies: Predominantly, intercalated bioclastic limestone and shale in the eastern part of offshore Abu Dhabi, where it attains its maximum thickness. In Central and western offshore Abu Dhabi, the predominant lithology is dolomite and sand. The Asmari Limestone also outcrops in Jabal Hafeet area in eastern part of Abu Dhabi, with nearly the same facies.

Boundaries: Both of the Upper and the lower boundaries with the overlying Lower Fars and the underlying Dammam Formations are conformable.

Age : Early Oligocene to Late Oligocene/Early Miocene (James & Wynd 1965; ADMA internal report)